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TITLE: REVENUE METER WITH POWER  
QUALITY FEATURES

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PATENT TRADEMARK OFFICE

## REVENUE METER WITH POWER QUALITY FEATURES

### REFERENCE TO RELATED APPLICATIONS

**[0001]** This application is a divisional application under 37 C.F.R. § 1.53(b) of U.S. Pat. Application Ser. No. 10/233,962, filed September 3, 2002 (Attorney Docket No. 6270/87) now U.S. Pat. No. \_\_\_\_\_, the entire disclosure of which, including the appendices, is hereby incorporated by reference herein. U.S. Pat. Ser. No. 10/233,962 being a divisional application under 37 C.F.R. § 1.53(b) of U.S. Pat. Application Ser. No. 09/370,317 filed August 9, 1999 (Attorney Docket No. 6270/22) now U.S. Pat. No. \_\_\_\_\_, the entire disclosure of which, including the appendices, is hereby incorporated by reference.

**[0002]** The following co-pending and commonly assigned U.S. Patent Applications have been filed on the same date as the above captioned U.S. Pat. Application Ser. No. 09/370,317. All of these applications relate to and further describe other aspects of the embodiments disclosed in the present application and are all herein incorporated by reference.

**[0003]** U.S. Pat. Application Ser. No. 09/371,883, "A-BASE REVENUE METER WITH POWER QUALITY FEATURES", (Attorney Ref. No. 06270/32), filed August 9, 1999, now U.S. Pat. No. 6,493,644.

**[0004]** U.S. Pat. Application Ser. No. 09/370,695, "REVENUE METER WITH GRAPHIC USER INTERFACE", (Attorney Ref. No. 06270/23), filed August 9, 1999, now U.S. Pat. No. \_\_\_\_\_;

**[0005]** U.S. Pat. Application Ser. No. 09/370,686, "REVENUE METER BLADE ASSEMBLY AND METHOD OF ATTACHMENT", (Attorney Ref. No. 06270/25), filed August 9, 1999, now U.S. Pat. No. 6,186,842;

**[0006]** U.S. Pat. Application Ser. No. 09/370,863, "A POWER SYSTEM TIME SYNCHRONIZATION DEVICE AND METHOD FOR SEQUENCE OF EVENT RECORDING", (Attorney Ref. No. 06270/24), filed August 9, 1999, now U.S. Pat. No. \_\_\_\_\_;

**[0007]** U.S. Pat. Application Ser. No. 09/369,870, "METHOD AND APPARATUS FOR AUTOMATICALLY CONTROLLED GAIN SWITCHING OF POWER MONITORS", (Attorney Ref. No. 06270/27), filed August 9, 1999, now U.S. Pat. No. 6,397,155;

**[0008]** U.S. Pat. Application Ser. No. 09/370,696, "EXTERNAL COMMUNICATIONS INTERFACE FOR A REVENUE METER", (Attorney Ref. No. 06270/26), filed August 9, 1999, now U.S. Pat. No. \_\_\_\_\_;

**[0009]** U.S. Pat. Application Ser. No. 09/370,757, "A KEYPAD FOR A REVENUE METER", (Attorney Ref. No. 06270/34), filed August 9, 1999, now U.S. Pat. No. \_\_\_\_\_.

#### REFERENCE TO MICROFICHE APPENDIX

**[0010]** A microfiche appendix, Appendix A, is incorporated by reference above of a computer program listing. The total number of microfiche is 6. The total number of frames is 186. A second microfiche appendix, Appendix B, is also incorporated by reference above of schematic diagrams. The total number of microfiche is 1 and the total number of frames is 23.

#### REFERENCE TO COMPUTER PROGRAM LISTINGS SUBMITTED ON COMPACT DISK

**[0011]** A compact disk appendix is included containing computer program code listings pursuant to 37 C.F.R. 1.52(e) and is hereby incorporated by reference. The compact disk contains program code files in ASCII format. The total number of compact disks is 1 and the files included on the compact disk are as follows:

Creation Date	Creation Time	File Size (Bytes)	File Name
07/06/1999	04:24p	4,004,514	v202fin.txt

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## FIELD OF THE INVENTION

**[0013]** This invention relates to revenue meters of the type used by energy suppliers to accurately measure electrical energy delivered to consumers for the purposes of billing and/or collecting revenue and more particularly, this invention relates to revenue meters having power quality monitoring, detection, quantification and reporting capabilities.

## BACKGROUND

**[0014]** In a typical electrical distribution system, electrical energy is generated by an electrical supplier or utility company and distributed to consumers via a power distribution network. The power distribution network is the network of electrical distribution wires which link the electrical supplier to its consumers. Typically, electricity from a utility is fed from a primary substation over a distribution cable to several local substations. At the substations, the supply is transformed by distribution transformers from a relatively high voltage on the distributor cable to a lower voltage at which it is supplied to the end consumer. From the substations, the power is provided to industrial users over a distributed power network that supplies power to various loads. Such loads may include, for example, various power machines.

**[0015]** At the consumer's facility, there will typically be an electrical energy meter ("revenue meter") connected between the consumer and the power distribution network so as to measure the consumer's electrical demand. The revenue meter is an electrical energy measurement device which accurately measures the amount of electrical energy flowing to the consumer from the supplier. The amount of electrical energy measured by the meter is then used to determine the amount for which the energy supplier should be compensated.

**[0016]** Typically, the electrical energy is delivered to consumers as an alternating current ("AC") voltage that approximates a sine wave over a time period. The term "alternating waveform" generally describes any symmetrical waveform, including square,

sawtooth, triangular, and sinusoidal waves, whose polarity varies regularly with time. The term "AC" (i.e., alternating current), however, almost always means that the current is produced from the application of a sinusoidal voltage, i.e., AC voltage. The expected frequency of the AC voltage, e.g., 50 Hertz ("Hz"), 60 Hz, or 400 Hz, is usually referred to as the "fundamental" frequency. Integer multiples of this fundamental frequency are usually referred to as harmonic frequencies.

**[0017]** While the fundamental frequency is the frequency that the electrical energy is expected to arrive with, various distribution system and environmental factors can distort the fundamental frequency, i.e., harmonic distortion, can cause spikes, surges, or sags, and can cause blackouts, brownouts, or other distribution system problems. These problems can greatly affect the quality of power received by the power consumer at its facility or residence as well as make accurate determination of the actual energy delivered to the consumer very difficult.

**[0018]** In order to solve these problems, revenue meters have been developed to provide improved techniques for accurately measuring the amount of power used by the consumer so that the consumer is charged an appropriate amount and so that the utility company receives appropriate compensation for the power delivered and used by the consumer. Examples of such metering systems are well known in the art.

**[0019]** While these conventional revenue accuracy type metering systems provide information about the quality of the power, i.e., frequency and duration of blackouts, brownouts, harmonic distortions, surges, sags, swells, imbalances, huntings, chronic overvoltages, spikes, transients, line noise, or the like, received by a power consumer at a particular consumer site, they fail to monitor and quantify the power quality with a sufficient level of detail. Blackouts, brownouts, harmonic distortions, surges, sags, swells, imbalances, huntings, chronic overvoltages, spikes, transients and line noise are all examples of power quality events. As utility companies become more and more deregulated, these companies will likely be competing more aggressively for various consumers, particularly heavy power users, and the quality of the power received by the power consumer is likely to be important. This, in turn, means that accurate and detailed reporting and quantification of power quality events and overall power quality will become more and more important as well.

**[0020]** For example, one competitive advantage that some utility companies may have over their competitors could be a higher quality of the power supplied to and received by the consumer during certain time periods. One company may promote the fact that it has fewer times during a month that power surges reached the consumer causing potential damage to computer systems or the like at the consumer site. Another company may promote that it has fewer times during a month when the voltage level delivered to the consumer was not within predetermined ranges which may be detrimental to electromagnetic devices such as motors or relays. Previous revenue accuracy meters which provide for measuring quality of power in general lack the necessary accuracy and features to provide the consumer and the power utility with the needed information.

**[0021]** Accordingly, there is a need for a revenue accuracy meter that is capable of monitoring, reporting and quantifying the quality of power with a high level of detail and accuracy. Further there is a need for a revenue accuracy meter that can continue to monitor and quantify data throughout the duration of a power quality event and prevent loss of recorded power quality information in the event of a catastrophic power quality event such as a complete power failure.

## SUMMARY

**[0022]** The present invention is defined by the following claims, and nothing in this section should be taken as a limitation on those claims. By way of introduction, the preferred embodiments described below relate to an energy meter for measuring the delivery of electrical energy from an energy supplier to a consumer through an electric circuit. The meter includes: a sensor coupled with the electric circuit and operative to sense the voltage in the electric circuit and generate an analog signal indicative of the voltage; an analog to digital converter coupled with the sensor and operative to convert the analog signal to one or more digital samples; a memory coupled with the analog to digital converter and operative to receive and store the digital samples; and a detector coupled with the memory and operative to compute a plurality of rolling voltages from the stored digital samples over an interval and to compare each of the plurality of rolling voltages to a threshold and indicate a sag/swell event when the rolling voltage deviates from the threshold.

**[0023]** The preferred embodiments further relate to an energy meter for measuring the delivery of electrical energy from an energy supplier to a consumer through an electric circuit. The meter includes: a draw-out chassis coupled with the meter and operative to fit within a switchboard enclosure; terminals disposed on the chassis for engaging matching terminals within the enclosure; a display; a meter cover operative to enclose the meter and the display within the enclosure; a seal connected with the meter cover and operative to prevent removal of the meter cover and indicate tampering with the meter; a sensor coupled with the electric circuit and operative to sense the voltage in the electric circuit and generate an analog signal indicative of the voltage; an analog to digital converter coupled with the sensor and operative to convert the analog signal to one or more digital samples; a memory coupled with the analog to digital converter and operative to receive and store the digital samples; and a detector coupled with the memory and operative to compute a plurality of rolling voltages from the stored digital samples over an interval and to compare each of the plurality of rolling voltages to a threshold and indicate a sag/swell event when the rolling voltage deviates from the threshold.

**[0024]** The preferred embodiments further relate to an energy meter for measuring the delivery of electrical energy from an energy supplier to a consumer through an electric circuit. The meter includes: a sensor coupled with the electric circuit and operative to sense a power parameter in the electric circuit and generate an analog signal indicative of the power parameter; an analog to digital converter coupled with the sensor and operative to convert the analog signal to one or more digital samples; a first memory coupled with the analog to digital converter and operative to receive and store the one or more digital samples; a first processor coupled with the analog to digital converter and further coupled with the first memory by a first data bus; a second processor coupled with a second memory by a second data bus; a bus arbiter responsive to the first and second processors and coupled with the first and second data busses, the bus arbiter operative to isolate the first data bus from the second data bus under normal operating conditions; and the bus arbiter further operative to couple the first data bus to the second data bus and perform a data transfer between the first memory and the second memory.

**[0025]** The preferred embodiments further relate to a revenue meter for measuring the delivery of electrical energy from an energy supplier to a consumer through an electric circuit. The meter includes: a draw-out chassis coupled with the meter and operative to fit within a switchboard enclosure; terminals disposed on the chassis for engaging matching terminals within the enclosure; a display; a meter cover operative to enclose the meter and the display within the enclosure; a seal connected with the meter cover and operative to prevent removal of the meter cover and indicate tampering with the meter; a first sensor coupled with the electric circuit and operative to sense the voltage in the electric circuit and generate a first analog signal indicative of the voltage; a second sensor coupled with the electric circuit and operative to sense the current in the electric circuit and generate a second analog signal indicative of the current; an analog to digital converter coupled with the first and second sensors and operative to convert the first and second analog signals to one or more digital samples; a memory coupled with the analog to digital converter and operative to receive and store the digital samples; and a calculator coupled with the memory and operative to compute one or more harmonic frequencies of the voltage and the current from the stored digital samples.

**[0026]** The preferred embodiments further relate to a revenue meter for measuring the delivery of electrical energy from an energy supplier to a consumer through an electric circuit, the electric circuit including at least one phase. The meter includes: a draw-out chassis coupled with the meter and operative to fit within a switchboard enclosure; terminals disposed on the chassis for engaging matching terminals within the enclosure; a display; a meter cover operative to enclose the meter and the display within the enclosure; a seal connected with the meter cover and operative to prevent removal of the meter cover and indicate tampering with the meter; one or more voltage sensors coupled with each of the at least one phase of the electric circuit and operative to sense the voltage in each of the at least one phase and generate an analog signal indicative of the voltage; one or more current sensors coupled with each of the at least one phase of the electric circuit and operative to sense the current in each of the at least one phase and generate an analog signal indicative of the current; at least one analog to digital converter coupled with the one or more voltage sensors and the one or more current sensors and operative to convert the analog signals to one or more digital samples at a rate of at least 64 samples per cycle;

a memory coupled with the analog to digital converter and operative to receive and store the one or more digital samples; and a processor coupled with the memory and operative to compute one or more fundamental voltage vectors from the magnitude and phase angle of the fundamental frequency of each of the voltage and the current and further operative to compute the zero, positive and negative sequence voltages by performing a vector addition of the one or more fundamental voltage vectors.

**[0027]** The preferred embodiments further relate to a revenue meter for measuring the delivery of electrical energy from an energy supplier to a consumer through an electric circuit. The meter includes: a draw-out chassis coupled with the meter and operative to fit within a switchboard enclosure; terminals disposed on the chassis for engaging matching terminals within the enclosure; a display; a meter cover operative to enclose the meter and the display within the enclosure; a seal connected with the meter cover and operative to prevent removal of the meter cover and indicate tampering with the meter; a sensor coupled with the electric circuit and operative to sense a power parameter in the electric circuit and generate an analog signal indicative of the power parameter; an analog to digital converter coupled with the sensor and operative to convert the analog signal to one or more digital samples at a rate of at least 64 samples per cycle; a first memory coupled with the analog to digital converter and operative to receive and store the one or more digital samples; a second memory coupled with the first memory; a power quality event detector coupled with the analog to digital converter and operative to detect a power quality event and generate a trigger signal; a holdoff timer coupled with the detector and operative to receive, delay and re-transmit the trigger signal; and a memory preservation mechanism coupled with the first memory, the second memory and the holdoff timer and operative to preserve the contents of the first memory using the second memory upon receipt of the trigger signal from the holdoff timer.

**[0028]** The preferred embodiments further relate to a revenue meter for measuring the delivery of electrical energy from an energy supplier to a consumer through an electric circuit. The meter includes: a draw-out chassis coupled with the meter and operative to fit within a switchboard enclosure; terminals disposed on the chassis for engaging matching terminals within the enclosure; a display; a meter cover operative to enclose the meter and the display within the enclosure; a seal connected with the meter cover and

operative to prevent removal of the meter cover and indicate tampering with the meter; a first power supply coupled with the electric circuit and operative to provide power to the meter from the electric circuit under normal operating conditions; and a second power supply operative to provide power to the meter when a power quality event occurs on the electric circuit, the second power supply including: at least one first capacitor coupled with the electric circuit and operative to store electrical energy from the electric circuit; and at least one second capacitor coupled with the at least one first capacitor and the meter and operative to store electrical energy from the electric circuit; the first and second capacitors further operative to provide the energy to the meter when the power quality event occurs.

**[0029]** The preferred embodiments further relate to a revenue meter for measuring the delivery of electrical energy from an energy supplier to a consumer through an electric circuit. The meter includes: a draw-out chassis coupled with the meter and operative to fit within a switchboard enclosure; terminals disposed on the chassis for engaging matching terminals within the enclosure; a display; a meter cover operative to enclose the meter and the display within the enclosure; a seal connected with the meter cover and operative to prevent removal of the meter cover and indicate tampering with the meter; a switching regulator coupled with the electric circuit and the meter and operative to convert the high voltage electrical energy to low voltage electrical energy; and a power supply coupled between the electric circuit and the switching regulator and operative to store the high voltage electrical energy and provide power to the meter when a power quality event occurs on the electric circuit.

**[0030]** The preferred embodiments further relate to a revenue meter for measuring the delivery of electrical energy from an energy supplier to a consumer through an electric circuit. The meter includes: a draw-out chassis coupled with the meter and operative to fit within a switchboard enclosure; terminals disposed on the chassis for engaging matching terminals within the enclosure; a display; a meter cover operative to enclose the meter and the display within the enclosure; a seal connected with the meter cover and operative to prevent removal of the meter cover and indicate tampering with the meter; and a power supply coupled with the electric circuit and the meter and operative to store energy from the electric circuit and provide the energy to the meter when a power quality

event occurs on the electric circuit, the power supply including: a high voltage portion coupled with the electric circuit and a low voltage portion coupled with the high voltage portion and the meter; and a processor coupled with the high voltage portion and operative to monitor the power supply and signal the meter when the stored power runs low.

**[0031]** The preferred embodiments further relate to a revenue meter for measuring the delivery of electrical energy from an energy supplier to a consumer through an electric circuit. The meter includes: a draw-out chassis coupled with the meter and operative to fit within a switchboard enclosure; terminals disposed on the chassis for engaging matching terminals within the enclosure; a display; a meter cover operative to enclose the meter and the display within the enclosure; a seal connected with the meter cover and operative to prevent removal of the meter cover and indicate tampering with the meter; and a power supply coupled with the electric circuit and the meter and operative to store energy from the electric circuit and provide the energy to the meter when a power quality event occurs on the electric circuit, the power supply including: a rectification circuit coupled with the electric circuit and operative to receive AC electric energy from the electric circuit and convert the AC electric energy to high voltage DC electric energy; a charge control circuit coupled with the rectification circuit; a first energy store coupled with the charge control circuit and operative to receive and store the high voltage DC electric energy from the rectification circuit at a rate controlled by the charge control circuit, the first energy store further operative to provide the stored high voltage DC electric energy to the meter when a power quality event occurs on the electric circuit; and a switching regulator coupled with the rectification circuit and the first energy store, the switching regulator operative to receive the high voltage DC electric energy from the rectification circuit and the first energy store, the switching regulator further operative to convert the high voltage DC electric energy to low voltage DC electric energy and provide the low voltage DC electric energy to the meter.

**[0032]** The preferred embodiments further relate to a method, in an energy meter for measuring the delivery of electrical energy from an energy supplier to a consumer through an electric circuit, for detecting sag/swell events. In one embodiment, the method includes: sensing the voltage in the electric circuit and producing an analog signal

indicative thereof; converting the analog signal to a plurality of digital samples; computing a rolling voltage from the plurality of digital samples each time a new digital sample is converted; comparing the rolling voltage to a threshold value; indicating a swell event when the rolling voltage exceeds the threshold value; and indicating a sag event when the rolling voltage is less than the threshold.

**[0033]** The preferred embodiments further relate to a method, in a revenue meter for measuring the delivery of electrical energy from an energy supplier to a consumer through an electric circuit, the electric circuit comprising at least one phase, for computing symmetrical components. In one embodiment, the method includes: providing a switchboard revenue meter including a draw-out chassis coupled with the meter and operative to fit within a switchboard enclosure, terminals disposed on the chassis for engaging matching terminals within the enclosure, a display, a meter cover operative to enclose the meter and the display within the enclosure and a seal connected with the meter cover and operative to prevent removal of the meter cover and indicate tampering with the meter; sensing the voltages in each of the at least one phase and generating analog signals indicative thereof; converting the analog signals to one or more digital samples at a rate of at least 64 samples per cycle; storing the digital samples in a memory; computing one or more fundamental voltage vectors from the magnitude and angle of the fundamental frequency of each of the sensed voltages from the stored digital samples; and performing a vector addition of the one or more fundamental voltage vectors to compute the zero sequence voltage.

**[0034]** Further aspects and advantages of the invention are discussed below in conjunction with the preferred embodiments.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0035]** Figure 1 depicts a perspective view of an exemplary S-Base revenue meter and socket type detachable meter mounting device for connecting the meter to an electrical circuit.

**[0036]** Figure 2 shows the blade type terminals on the back of the revenue meter depicted in Figure 1.

**[0037]** Figure 3 shows exemplary layouts of the matching jaws of the detachable meter mounting device of Figure 1 for receiving the blade type terminals shown in Figure 2.

**[0038]** Figure 4 depicts a perspective view of an exemplary A-Base revenue meter with bottom connected terminals for connecting the meter to an electrical circuit.

**[0039]** Figure 5 depicts a perspective view of an exemplary switchboard revenue meter and meter cover.

**[0040]** Figure 6 depicts a perspective view of the exemplary switchboard revenue meter of Figure 5 with the draw-out chassis removed.

**[0041]** Figure 7 depicts a block diagram of the power quality event detection, quantification and reporting hardware of the preferred embodiment revenue meter.

**[0042]** Figure 8 depicts a block diagram of the power quality event detection, quantification and reporting software of the preferred embodiment revenue meter.

**[0043]** Figure 9 depicts a block diagram of a preferred filter module of a power supply for use with the preferred embodiment revenue meter.

**[0044]** Figure 9A depicts a circuit schematic of the preferred filter module of Figure 9.

**[0045]** Figure 10 depicts a block diagram of a preferred switcher module of a power supply for use with the preferred embodiment revenue meter.

**[0046]** Figure 10A depicts a circuit schematic of the preferred switcher module of Figure 10.

**[0047]** Figure 11 depicts a preferred embodiment revenue meter for detecting transient events.

**[0048]** Figure 12 shows a block diagram depicting the transient detection module of the preferred embodiment revenue meter.

**[0049]** Figure 13 shows a block diagram depicting the Transient\_Detect\_PowerUp routine of the transient detection module of Figure 12.

**[0050]** Figure 14 shows a block diagram depicting the Transient\_Detect routine of the transient detection module of Figure 12.

**[0051]** Figure 15 shows a block diagram depicting the Scan\_For\_Deviant\_Samples routine of the transient detection module of Figure 12.

- [0052] Figure 16 shows a block diagram depicting DSP buffer comparison arrangement of the transient detection module of Figure 12.
- [0053] Figure 17 shows a block diagram depicting the Sag/Swell detection module of the preferred embodiment revenue meter.
- [0054] Figure 18 shows a block diagram depicting the Check\_Enable routine of the Sag/Swell detection module of Figure 17.
- [0055] Figure 19 shows a block diagram depicting the Initialize routine of the Sag/Swell detection module of Figure 17.
- [0056] Figure 20 shows a block diagram depicting the Initialize\_Disturbance routine of the Sag/Swell detection module of Figure 17.
- [0057] Figure 21 shows a block diagram depicting the Initialize\_Sub-Disturbance routine of the Sag/Swell detection module of Figure 17.
- [0058] Figure 22 shows a block diagram depicting the Read\_Inputs routine of the Sag/Swell detection module of Figure 17.
- [0059] Figure 23 shows a block diagram depicting the Detect\_Disturbance routine of the Sag/Swell detection module of Figure 17.
- [0060] Figure 24 shows a block diagram depicting the Write\_Disturbance\_Outputs routine of the Sag/Swell detection module of Figure 17.
- [0061] Figure 25 shows a block diagram depicting the Process\_Sub-Disturbance routine of the Sag/Swell detection module of Figure 17.
- [0062] Figure 26 shows a block diagram depicting the Augment\_Sub-Disturbance\_Data routine of the Sag/Swell detection module of Figure 17.
- [0063] Figure 27 shows a block diagram depicting the Augment\_Disturbance Data routine of the Sag/Swell detection module of Figure 17.
- [0064] Figure 28 shows a block diagram depicting the harmonics detection module of the preferred embodiment revenue meter.
- [0065] Figure 29 shows a block diagram depicting the data flow of the preferred waveform recording module.
- [0066] Figure 30 shows a block diagram depicting a portion of the waveform recorder firmware of the waveform recorder module.

[0067] Figure 31 shows a block diagram depicting the remaining portion of the waveform recorder firmware of the waveform recorder module.

[0068] Figure 32 shows a block diagram depicting the create and destroy behavior of the waveform recorder module.

[0069] Figure 33 shows a block diagram depicting the Direct Memory Access (“DMA”) firmware organization for the preferred embodiment revenue meter.

[0070] Figure 34 shows a half-cycle activity time for DMA accesses for the DMA firmware of Figure 33.

[0071] Figure 35 shows a flow chart depicting a typical DMA transaction.

[0072] Figures 36A-43L depict schematic diagrams of an exemplary measurement board of one preferred embodiment.

[0073] Figures 44A-48L depict schematic diagrams of an exemplary backplane board of one preferred embodiment.

[0074] Figures 49A-49L depict a schematic diagram of an exemplary power supply filter board of one preferred embodiment.

[0075] Figures 50A-50L depict a schematic diagram of an exemplary display board of one preferred embodiment.

[0076] Figures 51A-51L depict a schematic diagram of an exemplary power supply regulation board of one preferred embodiment.

[0077] Figures 52A-56L depict schematic diagrams of an exemplary communications board of one preferred embodiment.

## DETAILED DESCRIPTION OF THE DRAWINGS AND PRESENTLY PREFERRED EMBODIMENTS

### *I. Overview*

[0078] The preferred embodiments relate to highly accurate and detailed power quality event detection, monitoring and quantification in revenue accuracy electrical meters. Herein, the phrase “coupled with” is defined to mean directly coupled with or indirectly coupled to through one or more intermediate components.

[0079] Revenue accuracy electrical meters (“revenue meters” or “meters”) are metering devices that indicate or record electrical energy and demand (the average power

or a related quantity over a specified interval of time) for the purpose of compensating the electric utility for the energy consumption of the end user. Energy is typically the primary billing quantity and is equal to power integrated over time. Energy is measured in Kilowatt Hours (“KWH”) and demand is measured in Kilowatts (“KW”). Note that some consumers of electrical energy may also have generation capability. In a case where a consumer is generating more energy than he is consuming, that energy will flow back to the utility for which the consumer will be compensated. Effectively, a consumer with excess generation capacity becomes a supplier and the utility becomes the consumer. The methods, systems and apparatuses disclosed below are equally applicable to this alternative situation.

**[0080]** Revenue meters must comply with American National Standards Institute’s (“ANSI”) Standards for electric meters which include, but are not limited to, the following:

ANSI C12.1 (1995): American National Standard for Electric Meters-Code for Electricity Metering;

ANSI C12.10 (1987): American National Standard for Electromechanical Watthour Meters;

ANSI C12.13 (1991): American National Standard for Electronic Time of Use Registers for Electricity Meters;

ANSI C12.16 (1991): American National Standard for Solid-State Electricity Meters; and

ANSI C12.20 (1998): American National Standard for Electricity Meters 0.2 and 0.5 Accuracy Classes.

All of which are known in the art and are herein incorporated by reference.

**[0081]** Other specification/standards which apply to revenue meters include:

ISO Specification MTR1-96, “Engineering Specification for Polyphase Solid State Electricity Meters for Use on the ISO Grid”;

Consumer and Corporate Affairs Canada, Legal Metrology Branch,  
“Specifications for Approval of Type of Electricity Meters, Instrument Transformers and Auxiliary Devices”;

International Electrotechnical Commission, 687, “Alternating Current Static Watt-hour Meters for Active Energy (classes 0, 2 S and 0, 5 S)”;

Canadian Standards Association, C22.2 No. 115-M1989, “Meter Mounting Devices: Industrial Products”; and

Canadian Standards Association, CAN3-C17-M84, “Alternating-Current Electricity Metering: Electric Power Systems and Equipment”.

All of which are known in the art and herein incorporated by reference. It will be appreciated by those skilled in the art that there may be other applicable standards in use in the industry as well.

**[0082]** The ANSI standards define two general types of revenue meters, socket based (“S-base” or “Type S”) and bottom connected (“A-base” or “Type A”). A third type of revenue meter, known as a “Switchboard Meter” or “Draw-out Meter”, is also commonly in use in the industry. These types of revenue meters are distinguished, in at least one respect, by the method in which they are connected to the electric circuit that they are monitoring. All three meter types are designed for connection to a three phase electric circuit.

**[0083]** Referring now to Figures 1 through 3, an S-base revenue meter 100 is shown. Specifically, in Figure 1, the S-Base revenue meter 100 includes the revenue meter electronics 115, the meter cover 120 and the blade type terminals 125. The meter electronics further include a display 145 and input/output means 150. The input/output means 150 couples with the meter cover 120 when the cover is in place. The meter cover 120 includes a sealed input/output interface 155 which allows a user to interact with the input/output means 150. Also shown in Figure 1 is the detachable meter mounting device 130 and the sealing means 135. An exemplary S-base revenue meter 100 is the 8500 ION Revenue Meter manufactured by Power Measurement Limited, Saanichton, British Columbia, Canada. For more detail regarding the input/output means 150 and input/output interface 155, see the above referenced U.S. Pat. Application entitled “REVENUE METER WITH GRAPHIC USER INTERFACE”.

**[0084]** S-base meters 100 feature blade type terminals 125 disposed on back side of the meter as shown in more detail in Figure 2. These blade terminals are designed to mate with the matching jaws of a detachable meter mounting device 130 such as a

revenue meter socket as shown in more detail in Figure 3. Figure 3 shows two variations 130A and 130B of a meter socket as provided in the ANSI standards, although it will be appreciated by those skilled in the art that there are numerous varieties of revenue meter sockets. Referring back to Figure 1, the detachable meter mounting device 130 is hard wired to the electrical circuit (not shown) and is not meant to be removed. An exemplary detachable meter mounting device 130 is the 3000 Series Ring Type transformer rated meter socket manufactured by Meter Devices Co., Inc., Canton, Ohio. S-base meters 100 also have a cover 120 which encloses the meter electronics 115 and display 145. The cover has a sealing mechanism 140 which prevents unauthorized access to the meter electronics 115. Typically, this sealing mechanism 140 includes a lead wire “T” seal which is threaded through aligned holes in the sealing mechanism 140 and the base of the meter 100. To install the S-base meter 100, the utility plugs the meter 100 into the detachable meter mounting device 130. This makes installation of new meters, and especially replacement of defective meters, extremely simple. Once installed, the installer need only secure the sealing means 135 which ensure that the meter 100 will not be tampered with (as detailed in the ANSI standards). Exemplary sealing means 135 is the Screw Type Sealing Ring, Model 10-9090 manufactured by Ekstrom Industries, Inc., Farmington Hills, Michigan. The meter 100 further includes a flange 160A (The meter cover also has a flange 160B which fits together with flange 160A) and the detachable meter mounting device 130 includes a flange 165. The sealing ring fits around the flanges 160A, 160B and 165 and prevents them from separating. To remove or replace the meter 100, the installer need only remove the sealing means 135 and pull the meter 100 out of the socket. Alternatively, the sealing means 135 can be built into the detachable meter mounting device 130 as is the case with the 3000 Series Ringless Type transformer-rated meter socket manufactured by Meter Devices Co., Inc., Canton, Ohio. This meter socket features a cover with a port for the socket meter 100 that is narrower than flanges 160A and 160B on the meter 100. When the cover is installed, it prevents removal of the meter 100 from the detachable meter mounting device 130 and removal of the meter cover 120.

**[0085]** Referring to Figure 2, the blades 125 of the revenue meter 100 are shown in more detail. The blades 125 disposed on the back of the meter 100 connect the meter 100

to the electrical circuit (not shown) and allow the meter 100 to sense, measure and record the voltage and current. The smaller blades 125A in the middle of the meter 100 are used to sense voltage from the electric circuit. Voltage is sensed in parallel to the electric circuit, therefore only one set of inputs is necessary. The larger blades 125B located above and below the voltage blade inputs are used for the current inputs. Current is sensed in series with the electric circuit. The two sets of blades 125A, 125B provide a current return loop through the meter 100. It will be appreciated by those skilled in the art that other blade configurations are possible for voltage and current inputs and that other blades may also be used for other purposes such as communications.

**[0086]** Referring now to Figure 4, an A-base revenue meter 400 is shown. A-base meters feature bottom connected terminals 405 on the bottom side of the meter 400. These terminals 405 are typically screw terminals for receiving the conductors 410 of the electric circuit (not shown). A-base meters 400 further include a meter cover 415, meter electronics 420, a display 425 and input/output means 430. Further, the meter cover 415 includes an input/output interface 435. For more detail regarding the input/output means 430 and input/output interface 435, see the above referenced U.S. Pat. Applications entitled “REVENUE METER WITH GRAPHIC USER INTERFACE” and “A KEYPAD FOR A REVENUE METER”. A-base meters 400 are directly connected to the electric circuit and can only be installed or removed by connecting or disconnecting the conductors 410 of the electric circuit. Typically, this means tightening or loosening each terminal 405 to secure or free the end of the conductor 410. A-base meters 400 have a cover 415 which encloses the meter electronics 420 and the display 425. The cover 415 has a sealing mechanism (not shown in this figure but see Figure 2, Reference 140) which prevents unauthorized tampering with the meter electronics. Further, the base of the cover 415 also features a flange 440. The base of the meter 400 also features a flange 445. When the cover 415 is installed, the flanges 440 and 445 of the cover 415 and meter 400 can be sealed together with a sealing ring 450. An exemplary sealing ring 450 is the Screw Type Sealing Ring, Model 10-9090 manufactured by Ekstrom Industries, Inc., Farmington Hills, Michigan. Typically, A-base meters also have a second cover 455 and sealing mechanism (not shown) which encloses the terminal connections 405. This cover 455 and sealing mechanism prevents unauthorized disconnection of the A-base meter 400

from the electric circuit. It is also known in the art to provide a single sealing mechanism (not shown) which seals both the meter cover 415 and the terminal cover 455. For the purposes of this disclosure, A-base meters also include S-base meters in combination with A-base adapters. An A-base adapter is a self-contained S-base to A-base converter which features bottom connected terminals interconnected to a detachable meter mounting device, such as a meter socket, for receiving an S-base meter. An exemplary A-base adapter is the Polyphase Transformer Rated A to S Adapter manufactured by Ekstrom Industries, Incorporated, Farmington Hills, Michigan.

**[0087]** Referring now to Figures 5 and 6, there is shown a Switchboard Revenue Meter 500. The Switchboard meter 500 consists of a switchboard enclosure 505 (“enclosure”) which is physically mounted and connected to the electrical distribution system (not shown). Exemplary enclosures are the ABB FT-21 and ABB-FT-32 manufactured by ABB Electricity Metering, Raleigh, North Carolina. The revenue meter, which includes the meter electronics 510 and display 515, is mounted on a draw-out chassis 520 which is removable from the switchboard enclosure 505. The draw-out chassis 520 interconnects the meter electronics 510 with the electrical circuit. The draw-out chassis 520 contains electrical connections (See Figure 6, Reference 625 and 630) on the top and bottom which mate with matching electrical connectors (not shown) inside the enclosure 505 when the chassis 520 is slid into place. The enclosure 520 also has a cover 525 which completely seals the meter electronics 510 inside the enclosure 520. The cover has a sealing mechanism 530 which prevents removal of the cover 525 and indicates when the cover 525 has been tampered with. The cover 525 further includes a sealed input/output interface 535 which interconnects with input/output means 540 of the meter electronics 510. For more detail regarding the input/output means 540 and input/output interface 535, see the above referenced U.S. Pat. Applications entitled “REVENUE METER WITH GRAPHIC USER INTERFACE” and “A KEYPAD FOR A REVENUE METER”.

**[0088]** The relevant ANSI standards specify the exact physical and electrical requirements of the blade terminals for the S-base meters (See Figure 3) and the bottom connected terminals for the A-base meters. Further, these standards also specify revenue metering requirements common to both S-base and A-base meters as well as Switchboard

meters. These standards include accuracy, durability and operating lifetime requirements. They further include requirements for physically sealing the meters to prevent unauthorized tampering.

**[0089]** Referring again to Figures 1 through 6, revenue meters must provide sealing mechanisms 135, 140, 450, 455, 530 to both protect the meter from environmental conditions existing in the installed location as well as protect the meter from unauthorized tampering. Typically, A-base 400 and S-base 100 revenue meters are contained entirely within a housing which features a meter cover 120, 415 usually made of a transparent material. Typically, the enclosed components include the meter electronics 115, 420, voltage sensing circuits (not shown), current sensing circuits (not shown), the meter display 145, 425 and the user interface 150, 155, 430, 435 as specified by the ANSI standards. In typical applications, current transformers (“CT”) and potential transformers (“PT” or voltage transformer (“VT”)) are located remote from the revenue meter and connected with the meter’s internal voltage and current sensors via the S-base or A-base connection in order to isolate dangerous high voltage signals from the meter. In the exemplary 8500 ION Revenue Meter, an auxiliary set of CT’s is provided inside the meter to provide isolation. Potential (or Voltage) isolation in the exemplary 8500 ION Revenue Meter is accomplished with a network of resistors and op-amps. Further, it is well known in the art to provide revenue meters with external interface mechanisms such as telephony and network connections in order to enhance the meter’s capabilities.

**[0090]** Referring back to Figures 5 and 6, switchboard meters 500 are typically contained within a switchboard enclosure 505. The switchboard enclosure 505 usually features a cover 525 with a transparent face 545 to allow the meter display 515 to be read and the user interface 535, 540 to be interacted with by the user. The cover 525 also has a sealing mechanism 530 to prevent unauthorized access similar to the S-base and A-base meters.

**[0091]** The transparent meter cover 120, 415, 525, 545 permits the viewing of the meter display 145, 425, 515 without having to remove the meter cover 120, 415, 525. Further, the meter cover 120, 415, 525 may also provide mechanisms 155, 435 535 for interacting with the meter cover 120, 415, 525 in place. Such mechanisms 155, 435 535 include scroll buttons, reset switches or other input devices, and optical couplers, infrared

emitters or other output devices. All of these mechanisms are able to function with the meter cover 120, 415, 525 in place as specified in the ANSI standards. The meter cover 120, 415, 525 can be held in place by a separate sealing mechanism (See Figure 2, Reference 140) which locks the cover 120, 415 to the meter 100, 400 and indicates when there has been unauthorized tampering with the cover 120, 415. Typically, however, the sealing mechanism 135, 450, 530 also serves to lock the meter 100, 400, 500 to the electrical circuit connection. As shown in Figure 1, in the case of the S-base meter 100, the sealing mechanism 135 also seals the meter 100 to the meter socket 130. Removal of the meter 100 necessitates disengaging the sealing mechanism 135, which would indicate unauthorized tampering. As shown in Figure 4, in the case of the A-base meter 400, the sealing mechanism 450 also seals a separate (possibly joined) terminal cover 455 which prevents disconnection of the conductors 410 from the terminals 405 without disengaging the sealing mechanism 450. It should be understood that separate sealing mechanisms can be provided to seal the meter cover 415 and seal the meter 400 to the electrical connection and that other methods of tamper detection and environmental protection are well known in the art.

**[0092]** Power quality events are aberrations in the normal delivery of electrical power to the consumer. Normal delivery of electrical power is defined to be sustained delivery of electrical power at the specified fundamental frequency with minimal undesired harmonic frequencies present. The delivered electrical power has a specified voltage and a current which oscillates sinusoidally within a specified range at the defined fundamental frequency. Aberrations in the normal delivery of electrical power can last from a few nano-seconds (or shorter duration) to hours or days. These aberrations include complete power failures, voltage sags or swells, transient events and the presence of undesired harmonic frequencies. It will be appreciated that other aberrations in the delivery of electrical power are known to occur to those skilled in the art. The disclosed embodiments are directed at performing revenue metering functions while simultaneously detecting aberrations in the normal delivery of electrical power to the consumer as well as surviving and recording these aberrations for later diagnosis.

**[0093]** Figure 7 shows a preferred embodiment of a revenue meter 700 which can detect, record and report power quality events. Logically, the preferred embodiment

revenue meter is comprised of hardware and software. Figure 7 shows a typical hardware configuration where the meter 700 is connected to a three phase electric circuit 705. The meter 700 includes transducers 710 which sense the current and voltage in each phase of the electric circuit 705 and a power supply 715 which supplies power for the meter electronics (described in more detail below). The transducers 710 are also connected to an analog to digital (“A/D”) converter 720 which samples the current and voltage in each phase of the electric circuit 705. Note, as used herein, that the term A/D converter refers not only to a traditional A/D converters but also to a Time Division Multiplication (“TDM”) based converter, or other converter which converts analog signals to digital signals. TDM is a method of measuring instantaneous power over a wide range of input voltages. TDM is accomplished by taking a snapshot of the waveform of the incoming electrical signal and converting it to a square wave over time using a known algorithm. The area of this square wave is then proportional to the power at the time the snapshot was acquired. The snapshot or sample time is dependent on processor speed. An exemplary implementation of TDM is the Quad4-Plus Electric Meter manufactured by Process Systems, A division of Siemens Power and Transmission & Distribution, LLC, located in Raleigh, North Carolina which is described in the CD ROM specification for this product.

**[0094]** Referring back to Figure 7, the digital output of the A/D converter 720 is connected to a digital signal processor 725 (“DSP”). The DSP 725 is connected to memory 730 and to a central processing unit 735 (“CPU”). The DSP 725 in conjunction with the CPU 735 executes the power quality event detection and reporting algorithms as detailed below. Note that the preferred embodiment algorithms detailed below operate on samples as provide by the DSP 725 and CPU 735. These algorithms may operate on all samples provided or a subset of them. Typically, they operate utilizing 64 samples which represents  $\frac{1}{2}$  cycle. It will be appreciated however, that these computations can be performed with a greater or lesser number of samples (with the corresponding buffers adjusted accordingly), e.g. representing a quarter cycle or eighth of a cycle, down to a single sample. The processing power of the DSP 725 and CPU 735 is a limiting factor.

**[0095]** Continuing with Figure 7, the CPU 735 is also connected to a user interface 740 which allows users to program the meter 700 or retrieve revenue or power quality

data and generally interact with the meter 700. In the preferred embodiment, the user interface 740 includes a graphical display and a keypad as well as LED, infrared and optical interfaces. For more detail regarding the user interface 740, see the above referenced U.S. Pat. Applications entitled “REVENUE METER WITH GRAPHIC USER INTERFACE” and “A KEYPAD FOR A REVENUE METER”. It will be appreciated by those skilled in the art that the power quality detection and reporting algorithms detailed herein can be executed by a variety of hardware configurations, all of which are known in the art.

**[0096]** Figure 8 shows a block diagram depicting the power quality event detection 810 and reporting 820 software modules of the revenue meter 700. These modules, executed by the DSP 725 and CPU 735, provide the revenue meter 700 with the capability to detect, quantify, record, communicate and report power quality events. These modules include transient detection 815, wave shape deviation detection 820 (which is used by the transient detection algorithm 815), sag/swell detection 825, harmonic content detection 830 and symmetrical component detection 835.

**[0097]** The transient detection module 815 monitors the waveforms of all of the voltage phases of the electric circuit 705 for transient events. Should a transient event be detected, the transient detection module 815 determines its magnitude and duration. The wave shape deviation detection module 820 is used by the transient detection module 815. It predicts what the shape of the “normal” waveform should be and compares it to the actual waveform in real time. The sag/swell detection module 825 monitors the voltage inputs for disturbances. These disturbances typically appear as one or more of the inputs straying above a high limit or below a low limit. When a disturbance is detected, the module 825 provides information about the entire disturbance. The module 825 is also capable of breaking up the disturbance into discrete components (sub-disturbances) for more detailed analysis. The primary analysis performed is that of voltage quality monitoring. The harmonic content detection module 830 provides detailed harmonic calculations for voltage or current input. The symmetrical component detection module 835 provides information about unbalanced voltages and currents in a three phase power system. A more detailed description of these modules can be found in U.S. Pat. No. 5,650,936 which is herein incorporated by reference.

**[0098]** The reporting modules 850 include a waveform recorder 855 and a Direct Memory Access (DMA) control module 860. These software modules execute on the revenue meter hardware, sampling data, computing results and making those results available to the user. Each of the modules are user configurable and can be activated or deactivated depending on the needs of the user. Each module is discussed in detail below.

## *II. Power Supply and “Ride Thru”*

**[0099]** In revenue metering, an important capability is to be able to monitor, record and quantify as much of a power quality event as possible. One problem, however, is that most revenue meters receive their operating power from the same electric circuit which they are monitoring. Therefore, it is important that the occurrence of a power quality event not impact the meter’s performance. Maintaining meter performance during a power quality event is handled by the meter’s power supply.

**[00100]** Referring back to Figure 7, the power supply 715 is shown connected with the electric circuit 705. The power supply 715 supplies operating power to the revenue meter 700. However, as mentioned above, the power supply 715 is susceptible to the same power quality events that the meter 700 is designed to detect. The revenue meter 700 must be able to detect, quantify and report any power quality event, even those events which jeopardize the operating power of the meter itself. Therefore, the power supply 715 is also designed to provide short term isolation of the meter operation from the power quality event. This is known as “Ride-Thru” and enables the revenue meter 700 to continue to quantify and/or record and report the power quality event throughout the duration of the event and before losing operating power due to extended power quality events. Further, ride-thru capability permits the meter to ensure that critical power quality data is safely stored in non-volatile storage for later retrieval before the meter loses power and the data is lost.

**[00101]** Referring to Figures 9, 9A and 10, 10A, there is shown detailed block diagrams and schematics of the power supply of the preferred embodiment. The power supply is broken down into two modules, the switcher module 1000 and the filter module 900. The filter module 900, shown in block diagram form in Figure 9 and schematic form

in Figure 9A, includes metal oxide varistor transient suppression circuitry 905, three-phase (and Vref) EMI noise suppression filter circuitry 910, a three-phase (and Vref) full wave rectifier 915, Negative Temperature Coefficient (NTC) surge limiters 920, surge current limiters 925, a high energy capacitor bank 930, a low energy capacitor bank 935 and a relay 940. The switcher module 1000, shown in block diagram form in Figure 10 and in schematic form in Figure 10A, includes a high voltage wide range offline dc to dc switchmode converter 1005, a flyback transformer 1010, an output rectifier 1015, an output filter 1020, a voltage reference 1025 and a closed loop feedback control 1030, an energy management microcontroller 1035 and opto-isolators 1040 and 1045.

**[00102]** The revenue meter power supply provides a regulated and isolated dc supply voltage (+5V, up to 15 watts) that meets the energy requirements of the meter electronics. The power supply also functions to provide constant output voltage under abnormal input line conditions. An “abnormal” condition would include individual phase loss, line sags or swells, and limited-duration total (all three phases) loss of power or the occurrence of other power quality events. As described in more detail below, the ability to provide limited-time regulated output during a total power loss is made possible by the use of energy storage capacitors in combination with an onboard micro-controller based energy management system.

**[00103]** The power supply of the preferred embodiment includes a very wide operating range true three phase power supply. This permits the meter to operate with different input voltage conditions without necessitating different hardware. This allows a utility to stock fewer meter types in their inventory. Exemplary voltage inputs include three phase 120-277 Vrms +/- 20% (for a 4 wire Wye 9S connection) or 120-480 Vrms (for a three wire Delta 5S or 35S connection). Wye is a defined wiring system for three phase power where four power carrying conductors are used, one of which is a neutral conductor. Delta is a defined wiring system for three phase power utilizing three power carrying conductors. Either wiring system can include an extra safety ground conductor. Continuing with the power supply, multiphase operation also effectively reduces the power consumption of the meter by equally dividing the meter power requirements between each phase. In addition, true three phase operation provides the ability for the meter to continue normal operation with two out of three input phase loss (single phase

operation) in a four wire Wye configuration and the loss of a single phase in a three wire delta configuration.

**[00104]** Extended ride thru capability is provided through an internal high voltage capacitive energy store. This allows post event power quality measurement for a minimum of six cycles (100 ms) after complete power line loss. This also prevents a reset of the meter during power line disturbances.

**[00105]** The unique ride thru capability of the power supply, combined with an on-board energy management micro-controller, makes possible the effective use of inexpensive, high capacity, non-volatile flash memory to implement the meter's file system. The power supply provides power failure indication and sufficient ride thru time so that the flash based file system may be properly maintained and updated during power down events. The use of flash memory results in a significant cost savings on a cost/megabyte basis when compared with alternative volatile battery backed static random access memory. Flash memory does not require a power source for data retention.

**[00106]** As mentioned above, the power supply is divided into two circuit boards or modules; the filter board 900 and the switcher board 1000. Referring back to Figures 9 and 9A, the filter board 900 provides line filtering, three phase rectification and energy storage via high voltage electrolytic capacitors. The filter board is connected directly to the meter base voltage input terminals through an interconnecting cable assembly. Referring back to Figures 10 and 10A, the switcher board 1000 provides high voltage, wide range, isolated power conversion combined with micro-controller based energy management functions. The switcher board 1000 is connected to the filter board 900 via an interconnecting cable 1045 which supplies power to the flyback topology switcher circuitry. The switcher board 1000 is directly plugged into the main CPU backplane circuit board via a multi-pin connector 1050.

**[00107]** Referring back to Figures 9 and 9A, the filter board 900 accepts three phase voltage input plus neutral ( $V_{ref}$ ) and safety ground inputs. The input voltage range for three phase voltage is 120-277 Vrms L-N +/- 20% for a 4 wire Wye 9S connection or 120-480 Vrms L-L for a three wire delta connection. Capacitors C1-C5 and C14-C19 combined with inductors L1-L8 form a common and differential mode multi-phase line

filter. Conducted noise originating from the switching power supply is attenuated via the conducted path and external noise sources/transients are effectively reduced from entering the meter electronics. A high degree of filtering is required to eliminate self-generated conducted noise from polluting the meter's own voltage input lines which serve both the supply and measurement functions. Further, the high voltage diode array D1-D8 is arranged in the known three phase full wave bridge configuration. Diodes D4 and D8 are normally not conducting (no neutral current) unless a phase imbalance exists which can be the case when a phase is lost during a power quality event.

**[00108]** The energy reservoir capacitor bank 930 and 935 (C6-C9) combines conventional switch mode dc ripple filtering functionality together with energy storage for short term operation of the power supply during line loss events. This energy storage is divided between a low energy capacitor bank 935 (C6, C8) and a high energy capacitor bank 930 (C7, C9). Energy (measured in Joules) stored in each capacitor bank is a function of input voltage and capacitance as given by the formula:

$$E=1/2*C*V^2$$

**[00109]** The low energy capacitor bank 935 (C6, C8) has a total capacitance of 50 micro-farads ("μF") and under high voltage conditions (approximately 800 Vdc), provides a peak energy storage of 16 Joules. The high energy capacitor bank 930 (C7, C9) has a total capacitance of 195 μF, and under high voltage conditions (approximately 800 Vdc) provides a peak energy storage of 62.4 Joules. The capacitors of each bank are arranged in a series combination to achieve a high voltage rating capable of withstanding from 130 Vdc to 800 Vdc, depending on AC input line levels and phase relationships. Bleeder resistors R1-R4 equalize voltage imbalances across the series connected capacitor banks in addition to the removal or bleeding of hazardous voltages at power down.

**[00110]** The division of energy storage into two separate high and low energy capacitor banks 930 and 935 is fundamental to the successful operation of the revenue meter, particularly when the meter is being powered by the end user in calibration test fixtures as is typically done in utility company meter shops. Calibration test equipment is periodically used in end user service and verification roles for confirmation of revenue meter performance. These calibration test fixtures typically produce digitally synthesized three phase output voltage and current waveforms for both powering the meter and

providing the highly stable waveforms required for meter performance verification. The output voltage amplifiers in these test fixtures invariably suffer from overload when called on to supply the transient energy demand of a modern revenue meter, particularly when the meter incorporates a modern switch-mode power supply combined with large value energy storage capacitors. This transient or surge overload prevents current technology calibration test fixtures from powering a modern, high performance revenue meter, particularly at higher line voltages (such as 277 Vrms three phase). The problem is amplified by the fact that the majority of calibration test fixtures in the field were designed over 20 years ago when revenue meter internal energy requirements were much less demanding. Full backwards compatibility with traditional calibration equipment is a requirement of power utilities.

**[00111]** Referring back to Figures 10 and 10A, the switcher board 1000 receives high voltage DC input from the filter board 900. The supplied high voltage DC ranges in value from approximately 130 to 800 Vdc. This represents a more than 6:1 voltage change which is typically beyond the range of standard switching supplies. A discontinuous mode flyback converter is employed that operates beyond its traditional input voltage range of 3:1 without affecting the reliability of operation. This is done by changing its mode of operation with changes in input voltage and through the use of power MOSFETS with breakdown voltages of 1200 volts. The flyback transformer 1010 is specially constructed to meet the combined demands of small size and high voltage isolation capability. The high isolation voltages required of a multiphase, 277 Vrms L-N or 480 Vrms L-L offline switching supply places a particularly heavy demand on the supply flyback transformer. The transformer 1010 is wound on an industry standard, low cost ETD-29 bobbin using Phillips 3C85 magnetic material. A triple insulated Furukawa TEX-E wire is used for the secondary transformer windings. This provides a superior isolation barrier in excess of 5000 Vrms. The topology used in the power supply of the preferred embodiment revenue meter is based on Motorola Application Note AN1327 (herein incorporated by reference), with application specific modifications detailed below. The application note fully describes the operation of the power supply.

**[00112]** The power supply is based on a high performance current mode pulse width modulation (PWM) integrated circuit (IC). An exemplary PWM IC is the UC2844

IC, manufactured by Motorola, Schaumburg, Illinois, although it will be apparent to those skilled in the art that any UC2844 PWM IC will work such as those manufactured by Linfinity, Inc., or Unitrode, Inc. Conventional “bootstrap” operation of this IC simply requires a resistive connection to the high voltage DC input. This provides a minimum current (approximately .05 mA) which results in a Vcc voltage increase to the operating voltage of the IC. The minimum DC input voltage, combined with the minimum startup current (0.5 mA) essentially fixes the bootstrap resistor chain value. Under high line conditions (+800 Vdc) the resistive power dissipation becomes excessive, especially in the confined and airtight housing of a revenue meter. To minimize internal self heating, an active “bootstrap” or “startup” approach is taken. A high voltage MOSFET is biased at startup. After startup, the auxiliary winding of the flyback transformer produces a voltage which is rectified by a diode and regulated by a linear regulator producing +12 Vdc Vaux. The application of Vaux biases a transistor “on” which effectively turns another high voltage MOSFET “off”. The startup resistor chain is effectively removed from the high voltage DC supply which eliminates any additional long term power dissipation. Continued operation of the PWM IC is provided by the application of +12 Vdc Vaux through a forward biased diode.

**[00113]** A single chip micro-controller 1030 provides energy management by monitoring, in real time, the high voltage input to the switcher board. In the power supply of the preferred embodiment, the micro-controller 1030 is a PIC12C671, manufactured by Microchip, Inc. located in Chandler, Arizona. The measured voltage level effectively indicates the amount of energy stored in the input capacitor bank located on the filter board. The micro-controller 1030 also manages the delayed charging capacitor bank energy storage scheme. Unique to this power supply is that the micro-controller 1030 operates on the “high side” or non-isolated side of the supply. Signaling between the micro-controller 1030 and the main CPU backplane is accomplished via opto-isolators 1035 across the isolation barrier. This simplifies the accurate measurement of the capacitor bank voltage since the capacitor bank is also on the supply “high side.”

**[00114]** A regulator IC provides +5 Vdc for the micro-controller 1030 IC. A voltage monitor IC provides the system-reset signal to the micro-controller 1030 IC. High Voltage dc, ranging from +130-800 Vdc is applied to a series voltage divider

resistor string. The output of the divider ranges to a maximum of +5.0 Vdc and is applied to an A/D input on the micro-controller IC. The control algorithm executed by the micro-controller is straight forward. The high voltage dc input voltage is continuously digitized, with an 8 bit resolution, at a 1 ms rate. The digital value is compared to a hysteresis threshold window consisting of an upper and lower trigger point every 1 ms. If the high voltage average DC level drops below the lower trip point value, then port pin 6 of the micro-controller IC is asserted high. A transistor switch turns on an opto-isolator which in turn produces an active low interrupt signal to the CPU via the connector. This interrupt is de-asserted when the high voltage average DC level is greater than the upper trigger point.

**[00115]** When the supply AC input power fails (loss of line voltage), the high voltage DC level from the capacitor filter bank 930 and 935 decreases at a rate controlled by the meter power consumption. The meter continues to operate normally, with all aspects of power quality measurement continuing unabated. When the high voltage DC capacitor bank 930 and 935 voltage falls below the lower trigger point (120 Vdc), the meter's CPU is immediately interrupted with the highest priority interrupt. All operation is suspended, non-critical peripheral devices are powered down, and power quality data is written to the flash memory followed by the meter being placed in low power sleep mode. A general meter reset occurs with the return of +5.0 Vdc supply on re-application of input AC power. The meter may also be reset if, on entering sleep mode, the input AC power returns before there is a general loss of +5.0 Vdc supply. In this case, a hardware watchdog timer will reset the meter after approximately 0.5 seconds since the watchdog timer is not being serviced by the sleeping CPU.

**[00116]** The lower trigger point (120 Vdc) is selected to provide sufficient time for the meter operating system to suspend operation and write critical power quality data to the flash memory before the loss of the main supply voltage. The upper trigger point (130 Vdc) is selected to provide a hysteresis window in order to prevent inadvertent assertion of the interrupt signal due to system noise.

**[00117]** Operation of power supply in the preferred embodiment is as follows. On initial application of power, the capacitor isolation relay 940 (RLY1) is open and the high energy bank 930 (C7, C9) is charged over a 5 second period up to the maximum

operation voltage through resistors R5 and R6. The 5 second time constant effectively limits the peak power surge (Peak Energy/5 seconds) required to charge the high energy capacitor bank 930 to levels acceptable by traditional calibration test fixtures. The low energy capacitor bank 935 (C6, C8) is charged rapidly, with a time constant and surge current limiting action provided by Negative Temperature Coefficient Thermistor (“NTC”) current limiters 920 (NTC1 and NTC2). The peak power required by the low energy capacitor bank 935 during charging is limited by the NTC surge resistance and the fact that the low energy bank 935 capacitance is significantly lower than the high energy bank 930. After a five second delay, the micro-controller 1030 on the switcher board activates relay 940 (RLY1) which connects the low and high energy capacitor banks 930 and 935 in parallel. The high and low energy capacitor banks 930 and 935 are effectively combined and at this point in time the power supply is now able to provide the required ride thru time through the combined bank energy storage. An advantage to this switching scheme is that, on initial power up, the low energy capacitor bank 935 is rapidly charged and the power supply operating voltage (+5 Vdc) is available in less than 200 ms. The main meter can therefore begin the code booting sequence with full operation commencing after the 5 second charging delay.

**[00118]** The large combined capacitance value (245 uF) provided by the combined capacitor banks 930 and 935, once charged after the 5 second delay, serves as a temporary energy storage reservoir in the event of a power loss. This equates to approximately 6 cycles or 100 ms additional operating time at low line (96 Vrms, 60 Hz) and single phase worst case conditions (see the equation for energy stored above). For high line (277 Vrms) three phase normal operation, the operating time from power failure can be as high as approximately 15 seconds. The exact time period is a function of meter power consumption and varies depending on installed hardware options.

**[00119]** In addition, detailed schematics of the power supply of the preferred embodiment are included herein as microfiche appendix B and as Figures 36A-56L.

**[00120]**

### *III. Power Quality Event Detection*

#### *a. Transient Detection*

**[00121]** The transient detection module monitors the waveforms for all of the voltage phases of the electric circuit. Upon detection of a transient event, the module will determine its magnitude and duration. A transient is a momentary variation in the voltage and/or current, which ultimately disappears. Transients encompass spikes, sags, swells, blackouts, noise as well as other momentary fluctuations in the delivered electrical energy. Note that while sags and swells are considered transient events, they typically last longer than one cycle and therefore, in the preferred embodiment, detection of these events are handled by a separate algorithm. A transient usually lasts for less than one cycle or 16 ms. It is very important to be able to detect and report transient events while providing revenue accurate energy and power measurements.

**[00122]** In the preferred embodiment, transient detection is broken down into two parts. The digital signal processor (“DSP”) side and the central processing unit (“CPU”) side. Referring now to Figure 11, there is shown a preferred embodiment of a revenue meter 1100 for detecting transient events from a three phase electric circuit 1105. The revenue meter includes current transducers 1110 (“CT”) and voltage transducers 1115 (“PT”) coupled with the electric circuit 1105 and an analog to digital (“A/D”) converter 1120 for sampling the voltage and current from each phase of the electric circuit 1105 and converting them to digital samples. Two reference buffers 1125 and 1130 for each phase, described in more detail below, are further provided to hold digital samples for comparison. The revenue meter also includes a DSP 1135 and a CPU 1140 as well as memory 1145 and a user interface 1150. The DSP 1135 executes the transient detection algorithms as described below and supplies the results to the CPU 1140. The CPU 1140 then supplies the results to the user via the user interface 1150. An exemplary DSP 1135 is the TMS 320C203 manufactured by Texas Instruments, Inc., located in Dallas, Texas. An exemplary CPU 1140 is the Power PC MPC821, manufactured by Motorola, Inc., located in Schaumburg, Illinois.

**[00123]** The DSP 1135 samples voltages from the overvoltage gain stage which is connected to the electric circuit 1105 and transients are detected using the algorithm detailed below. In the exemplary revenue meter 1100, the overvoltage range for the

overvoltage gain stage is 1000V or greater. Alternatively, other voltage ranges can be used as well. The DSP samples the voltage at a rate of 128 samples per cycle to achieve a 130 micro-second resolution at 60 Hz. It is preferable that the sampling frequencies range from 18-72 Hz and more preferable that the sampling frequencies range from 20-70 Hz. It will be appreciated that sampling rates as low as 32 samples per cycle can also be used. The results of the algorithm are passed to the CPU 1140 via direct memory access. Alternatively, other methods of sharing data between the CPU 1140 and DSP 1135 can also be used. The CPU 1140 manages and stores the results for later user access.

**[00124]** The transient detection algorithms also prevent duplicative results when sag or swell events occur. This is because when a sag or swell occurs, sometimes it will not be detected as a sag or swell until the second cycle of the event. By this time, however, a transient, in the first cycle of the sag or swell, would have already been detected. To prevent duplicative reporting of both a transient and a sag or swell, the transient detection algorithm does not report the transient immediately. The algorithm will wait for the next cycle of samples and report based on the aggregate results of the two cycles. The sag and swell detection algorithm can utilize this reporting delay to suppress reporting of the transient once it detects a sag or swell occurring.

**[00125]** Referring now more specifically to Figure 11, there is shown a block diagram depicting the transient detection mechanism. The A/D converter 1120 samples voltages from each phase of the electric circuit 1105 via the current and voltage transducers 1110 and 1115. The voltages are converted to digital samples and stored in a current cycle buffer 1155 on the DSP 1135. According to the algorithms detailed below and in the Figures, the DSP compares the samples stored in the current cycle buffer with the samples stored in the reference buffers 1125 and 1130. There are two reference buffers, an even buffer 1125 and an odd buffer 1130. Depending on whether the current cycle is even or odd, the DSP compares the current cycle with the contents of the proper reference buffer. Differences between the reference sample and current sample are stored in a difference buffer 1160.

**[00126]** Figures 12 through 14 detail the algorithm used by the preferred embodiment to detect transient events. Figure 12 shows a top level view of the algorithm as broken up into a power up routine (Block 1205) and a one cycle transient detection

task (Block 1210) which executes every one cycle. It will be appreciated that the transient detection task can execute at other intervals. Figure 13 shows the blocks executed by the meter when power is first applied. First, the A/D\_Count\_Threshold is set to the maximum value (Block 1305). During execution of the transient detection algorithm, this value is calculated dynamically (as detailed below) and will be used to compare with samples from the electric circuit to determine if a transient has occurred. Initially, this value is set to the maximum to prevent the detection mechanism from detecting transients during this power up phase. Next, a one second delay timer is set to delay calculation of the A/D\_Count\_Threshold value (Block 1310). Finally, the algorithm outputs are set to a not\_available state and the holdoff counter is initialized to four (Block 1315). The holdoff counter is used to prevent duplicative reporting of transient events due to transient echoes as detailed below. Transient echoes are defined as the condition where the reference samples/buffers (see below) contain a transient that has already been reported.

**[00127]** Referring once again to Figure 12, once the power up routine (Block 1205) is complete, the meter will begin executing the transient detection algorithm (Block 1210). In the preferred embodiment, the transient detection algorithm is executed on every cycle. Alternatively, the algorithm can be executed according to a longer or shorter interval.

**[00128]** Figure 14 shows the details of the transient detection algorithm which is executed on every cycle. It is first determined if the transient detection algorithm is enabled (Block 1405). If it is not enabled then the hold off counter for all phases of the power input is initialized and the output registers are set to a “not available” state (Block 1410). The holdoff counter is used to prevent duplicative reporting of transient events from the detection of transient echoes and the back ends of sag and swell events. The hold off counter is a count down timer which prevents detection of transient events during the count down period. In the preferred embodiment, the hold off time period is set to 4 cycles although it will be appreciated by those skilled in the art that a longer or shorter duration can be used. Finally, a cycle counter is incremented (Block 1415) and the routine ends for the current cycle. The cycle counter is used by the sample comparison

routine to determine whether this is a even or odd cycle, as described in more detail below.

**[00129]** If the transient detection module is enabled, it is next determined whether there is nominal voltage input available (Block 1420). If there is no nominal voltage input, the routine sets the output registers to the unavailable state, sets the hold off counter to four cycles for all phases, increments the cycle counter and the routine ends for the current cycle (Blocks 1410, 1415). If the nominal voltage input is available or non-zero, the routine checks to see if it has been at least one second since the A/D\_Count\_Threshold (“threshold”) has been calculated (Block 1425). The threshold is used to compare with the sampled voltage values to determine whether a transient is occurring. This threshold is computed dynamically every 1 second. Alternatively, longer or shorter delays can be used for re-computing the threshold. If it has been one second since the last threshold calculation, the threshold is re-calculated according to the following formula (Block 1430):

$$\text{A/D\_Count\_Threshold} = \text{Transient Module Threshold \%} * \text{Normal\_A/D\_Peak}$$

$$\text{Where Normal\_A/D\_Peak} = \text{Nominal\_A/D\_Peak} * \frac{(\text{PT\_Secondary/Meter Input Voltage})}{(\text{nominal voltage/PT Primary})}$$

Transient Module Threshold %: The amount that the voltage can deviate from normal before a transient is reported. This value is expressed as a percentage of nominal voltage.

Normal\_A/D\_peak: The analog to digital (“A/D”) converter value for the peak sample of the voltage waveforms that would occur when the voltage waveform is purely sinusoidal with a magnitude equal to the nominal voltage.

Nominal\_A/D\_peak: The A/D converter value for the peak sample of a sinusoidal voltage input that is applied at the rated meter input voltage. This value is preferably equal to 4095.

Meter Input Voltage: The rated maximum voltage that can be applied at the voltage terminals.

Nominal Voltage: The nominal operating voltage in the power system (i.e., the AC power line voltage).

PT Secondary: The voltage rating on the Potential Transformer secondary winding.

PT Primary: The voltage rating on the Potential Transformer primary winding.

**[00130]** Once the threshold is calculated, or if it has not yet been 1 second since the last threshold computation, the routine sets the phase to be examined for a transient event to phase A (Block 1435). The blocks following this block will be repeated for each phase of the electric circuit being monitored. It is then determined whether or not the holdoff counter for this particular phase is less than or equal to zero (i.e., has counted down 4

cycles) (Block 1440). If the hold off counter for this phase is not less than zero, the holdoff counter is decremented (Block 1445), the Duration output register is set to 0 and the Max output register is set to 100 for this phase (Block 1450). This avoids reporting transient echoes. If all three phases have been processed at this point (Block 1455), the Nominal output is copied to the TranNominal Output (Block 1460), the cycle count is incremented (Block 1415) and the routine ends for the current cycle. The cycle count is used to control which reference buffer will be used in the waveshape deviation routine (See below). If all of the phases have not yet been processed (Block 1455), the routine advances to the next phase (Block 1465) and returns to check the holdoff counter for this next phase.

**[00131]** If the holdoff counter for the current phase undergoing analysis is less than or equal to zero (Block 1440), then the routine checks to see if there is a transient present by executing the Scan\_For\_Deviant\_Samples algorithm (Described in more detail below) (Block 1470). If a transient is not detected in the current cycle (Block 1475), it is determined whether or not a transient occurred in the previous cycle (Block 1480). If there was no transient in the previous cycle, then the Duration output register is set to 0 and the Max output register is set to 100 for this phase (Block 1450). This indicates that no transient is present. If all three phases have been processed at this point (Block 1455), the Nominal output is copied to the TranNominal Output (Block 1460), the cycle count is incremented (Block 1415) and the routine ends for the current cycle. At this point, all three phases have been checked for transients for the current cycle. If all of the phases have not yet been processed, the routine advances to the next phase and returns to check the holdoff counter for this next phase. If a transient is detected in the current cycle and there was no transient in the previous cycle (Block 1485), the cycle count is incremented (Block 1415) and the routine ends for the current cycle.

**[00132]** Whether or not there is a transient in the current cycle, if there was a transient in the previous cycle (Block 1485), the Duration and Max output registers for the current phase under analysis are written, aggregating the results of the current and prior cycle if necessary. The trigger output for this phase is pulsed and the Anytrig output is pulsed. This triggers the waveform recorder and the data recorder to store transient information if any phase has a transient. Further, the event is written into the event log if

EvPriority is greater than zero. EvPriority is a value set by the user and is used to control the reporting of transients based on the severity of the transient. This variable has a range from 0-255 where a value of zero will suppress transient reporting. Alternatively, other value ranges can be used and other values can be used to indicate transient reporting suppression. Finally, the holdoff counter for this phase is reset back to 4 (Block 1490). If all three phases have been processed (Block 1455), the Nominal output is copied to the TranNominal Output (Block 1460), the cycle count is incremented (Block 1415) and the routine ends for the current cycle. *At this point, all three phases have been checked for transients for the current cycle.* If all of the phases have not yet been processed (Block 1455), the routine advances to the next phase (Block 1465) and returns to check the holdoff counter for this next phase.

**[00133]** As can be seen from the algorithm, transients are detected on each phase within a window of one cycle. Further, transient reporting is delayed by one cycle. This prevents duplicative reporting of transient events due to sags and swells as well as transient echoes by giving the sag/swell detection routines a one cycle delay to suppress transient reporting. The sag/swell module will disable transient reporting when it detects a sag/swell event (discussed in more detail below).

b. Wave Shape Deviation Detection

**[00134]** Referring now to Figures 15 and 16, there is shown an algorithm for detecting transient events on an input waveform as well as a block diagram illustrating the comparison method. The wave shape deviation module predicts what the shape of the “normal” waveform should be and compares this predicted waveform to the actual waveform. Any detected deviations which exceed a given threshold will be reported. This routine is called by the transient detection algorithm (Figure 14, Block 1470) which provides the current phase undergoing analysis as well as the current value of the dynamically calculated threshold for determining whether there is a transient occurring. As described above, the threshold is computed dynamically every one second.

**[00135]** The routine first selects the buffer holding the digital samples for the current cycle for the voltage phase currently being analyzed (Block 1505) (See also Figure 11). It is next determined which reference buffer will be used to compare to the

current cycle buffer (Block 1510). This determination is based on whether the current cycle is even or odd utilizing the current cycle count. This is done so as to compare the current cycle data with data from two cycles earlier. It will be appreciated that any previous cycle that is non-consecutive (i.e. more than one cycle earlier) with the current cycle can also be used to perform the comparison. In this way, non-consecutive cycles are compared with each other. Figure 16 shows a block diagram of the buffer comparison arrangement. These buffers hold 128 samples due to the sampling frequency of 128 samples per cycle. Alternatively, a higher or lower sampling rate can be used or the buffers could store only a subset of the sampled data. Once the appropriate reference buffer is chosen (Block 1510), each sample from the current cycle is compared with the corresponding non-consecutive sample in the reference buffer and an absolute difference for each sample is computed and stored in a difference buffer (Block 1525). The difference buffer also has 128 elements.

**[00136]** Next, the contents of the current cycle buffer are copied to the reference buffer for comparison 2 cycles later (Block 1530). The routine then compares each sample in the difference buffer with the threshold value and counts the number of samples which exceed the threshold (Block 1535). This is the deviant sample count. The maximum difference/deviation between any one sample and the threshold is also computed (Block 1535). The deviant sample count and the maximum deviation are then passed back to the transient detection algorithm. This data is sent to the CPU via direct memory access (DMA) (See below for further detail). Note that in the preferred embodiment, the current cycle wave shape is compared with the wave shape from 2 cycles prior, however, it will be apparent to one of ordinary skill in the art that the comparison of the current cycle can be with any prior non-consecutive cycle's waveshape.

c. Sag/Swell Detection

**[00137]** The sag/swell module monitors voltage inputs for disturbances (for example, where one or more inputs strays above a high limit or below a low limit). When a disturbance is detected, the module provides information about the entire disturbance. The module can also break up the disturbance into discrete components or sub-

disturbances for more detailed analysis. This module provides data for detailed historical analysis of power quality.

**[00138]** Voltage sags occur when the AC power line voltage drops below its rated or specified level. Conversely, disturbances where the line voltage exceeds its rated or specified level are referred to as voltage swells. A sag is typically considered a momentary 15% to 100% reduction in the RMS voltage of an AC power source while a swell is a similarly characterized increase. Sags and swells typically have a minimum duration of two cycles. In detecting sags and swells, it is important that identical sags and swells repeatedly applied to different points on the waveform all be detected and consistently quantified. It is also important that the quantified data be of sufficient accuracy to be used for financial settlements.

**[00139]** In the preferred embodiment, a root mean square (“RMS”) voltage is computed on a rolling basis over a window which moves each time a sample is added. The preferred measurement window for sag/swell detection is one cycle because this is the shortest measurement window that is not affected by even harmonics.

**[00140]** The RMS value is computed by buffering all of the samples over the measurement window and computing the RMS of all of the samples over the measurement window. With the rolling RMS method of the preferred embodiment, this value is recomputed each time a new sample is acquired by moving the computation window to include the newest sample and exclude the oldest sample. After each calculation update, the computed value is compared to sag and swell threshold values to determine if a sag or swell has occurred, is continuing or has ended. In the preferred embodiment, a running squared sum value is computed for the window. With each new sample, the square of the new sample is added to the running sum and the square of the oldest sample value is subtracted out. The running sum is then used for comparison. It will be appreciated by those skilled in the art that other methods can be used to compute a rolling RMS value. The preferred method is executed at least 16 times per cycle. It will be appreciated that other computation intervals can be used as long as the interval is frequent enough to achieve a sub-cycle rolling window. The interval can range all the way down to the time difference between two successive samples.

**[00141]** Figures 17 through 27 show a flow chart for a top level of a preferred sag/swell detection algorithm. The algorithm can operate every one-half cycle with respect to the power system frequency or, alternatively, every one second. Figure 17 shows the overall operation. This includes the following subroutines: Check\_Enable (Block 1705), Read\_Voltage\_Inputs (Block 1710), Detect\_Disturbance (Block 1715), Write\_Disturbance\_Output\_Registers (Block 1720), Process\_Sub-Disturbance (Block 1725), Augment\_Sub-Disturbance\_Data (Block 1730), and Augment\_Disturbance\_Data (Block 1735).

**[00142]** The top level routine first calls the check\_enable subroutine (Figure 18) to determine if sag/swell detection is enabled. The register linked to the enable input of the module is read (Block 1805). If the module is enabled, control returns to the main routine (Block 1810). If the module is not enabled, then the initialize sub-routine (Figure 19) is called (Block 1815). Referring to Figure 19, in the initialize sub-routine, the value of the disturbance state output register is checked (Block 1905). If this value is anything other than not\_available, the initialize routine calls the initialize disturbance data sub-routine (Block 1910) which, referring to Figure 20, initializes the following internal variables for each phase (Block 2005):

Input\_state = DIST\_NONE

Min\_output = Max\_long

Max, ave., energy, num\_periods = 0

**[00143]** Referring back to Figure 19, following the initialize disturbance data subroutine (Block 1910), the initialize subroutine calls the initialize sub-disturbance data subroutine (Block 1915) which, referring to Figure 21, initializes the following internal variables for each phase (Block 2105):

Sub-dist ave = 0

Sub-dist num\_periods = 0

The initialize subroutine then exits.

**[00144]** Referring back to Figure 19, if disturbance state output register value is not-available (Block 1905), this indicates that this is the first time the sag/swell module has been initialized. All of the boolean and numeric output registers are set to not\_available (Block 1920). It is next checked whether or not a disturbance was in progress (Block 1925). If there was no disturbance in progress, an information event is

written and the initialize disturbance data (Block 1910) and initialize sub-disturbance data (Block 1915) subroutines are called as detailed above (Block 1930). The information event indicates an abnormal input condition that may require user attention. If there was a disturbance in progress, an event is written with priority equal to Event\_Pri (Block 1935) and the initialize disturbance data (Block 1910) and initialize sub-disturbance data (Block 1915) subroutines are called as detailed above. The event is written to indicate that the routine is no longer capable of detecting the sag/swell due to the abnormal input condition. The sag/swell routine then ends for the current detection period.

**[00145]** Referring back to Figure 17, if the sag/swell module is enabled, the initialize routine will return control back to the next block to read the voltage inputs. Referring now to Figure 22, there is shown a detailed block diagram of the read\_voltage\_inputs\_sub-routine. It is first determined whether or not one second has elapsed since the last reading of the nominal voltage (Block 2205). If not, and if sag/swell detection is not enabled (Block 2210), then the routine exits for the current detection period. If sag/swell detection is enabled, it is determined if any selected voltage input is not available (Block 2215). If the selected voltage input is available, then the voltage inputs are read, cast to unsigned 32 bit numbers and saved to internal storage (Block 2220). Next the internal V1-V3 are multiplied by 256 to insure that a 1% voltage resolution is maintained (Block 2225). These are then normalized with respect to the internal nominal voltage and saved to internal storage. Control is then returned to the top level routine (Figure 17). If any selected voltage input is not available (Block 2215), then the read inputs routine passes control to the initialize routine (Block 2230) (Figure 19 and detailed above). Once the initialize routine completes, control returns to the top level (Figure 17).

**[00146]** If one second has elapsed since the last time the nominal voltage was read (Block 2205), the nominal voltage is read and stored in temporary storage (Block 2235). The one second delay is used to reduce processing power needs. If the nominal voltage is less than or equal to zero or not available (Block 2240), sag/swell detection is disabled (Block 2245), the initialize routine is called (Block 2250) (Figure 19 and detailed above) and the routine exits for this detection period. If the nominal voltage is greater than zero (Block 2240) then the nominal voltage is cast into an unsigned 32 bit number and stored

in internal storage (Block 2255). It is next checked if the VoltsMode input is linked (Block 2260). Voltsmode defines the wiring configuration of the meter (Delta or Wye, etc.) and instructs the module which voltage inputs have valid RMS data. Linking the Voltsmode is a software mechanism for backwards compatibility with meters which cannot automatically detect the wiring configuration and allows the software to pick up the value from a register set at the time the meter was configured.

**[00147]** If the VoltsMode input is not linked, the voltage inputs, V1-V3 are selected and control is passed through the next blocks to determine if any selected voltage input is not available (Blocks 2265, 2270, 2210, 2215). If the selected voltage input is available, then the voltage inputs are read, cast to an unsigned 32 bit number and saved to internal storage (Block 2220). Next the internal V1-V3 are multiplied by 256 to insure that a 1% voltage resolution is maintained (Block 2225). These are then normalized with respect to the internal nominal voltage and saved to internal storage. Control is then returned to the top level routine (Figure 17). If any selected voltage input is not available, then the read inputs routine passes control to the initialize routine (Block 2230) (Figure 19 and detailed above). Once the initialize routine completes, control returns to the top level (Figure 17).

**[00148]** If the VoltsMode input is linked (Block 2260), then it is checked whether or not the VoltsMode has changed (Block 2275). If it has changed, then the initialize routine is called (Block 2280) (Figure 19 and detailed above). If it has not changed or once the initialize routine completes, the voltage inputs are selected based on the register linked to the VoltsMode input (Block 2285). Control is then passed through the next blocks to determine if any selected voltage input is not available (Blocks 2270, 2210, 2215). If the selected voltage input is available, then the voltage inputs are read, cast to an unsigned 32 bit number and saved to internal storage (Block 2220). Next the internal V1-V3 are multiplied by 256 to insure that a 1% voltage resolution is maintained (Block 2225). These are then normalized with respect to the internal nominal voltage and saved to internal storage. Control is then returned to the top level routine (Figure 17). If any selected voltage input is not available, then the read inputs routine passes control to the initialize routine (Block 2230) (Figure 19 and detailed above). Once the initialize routine completes, control returns to the top level (Figure 17).

**[00149]** Figure 23 shows a flow chart depicting the detect\_disturbance subroutine. The routine first checks each configured voltage input (Block 2305). For each input, it is determined whether or not the voltage is within the sag and swell limits (Block 2310). If it is not within these limits, the input state is set to either Dist\_Start state or Dist\_Continuing state (Block 2315). If prior to this point, the input state was already in Dist\_Start or Dist\_Continuing, then the input state will be set to Dist\_Continuing. If not, then the input state will be set to Dist\_Start. If the voltage is within the sag and swell limits, then the input state is set to either Dist\_End or Dist\_None (Block 2320). If the prior state of the input state was Dist\_Start or Dist\_Continuing then the input state will be set to Dist\_End otherwise it will be set to Dist\_None.

**[00150]** Once all inputs have been checked (Block 2325), an aggregate input state from all input is determined (Block 2330). The aggregate state is computed by OR'ing all of the inputs together. If the aggregate state is Dist\_Start (Block 2335), then the disturbance start time is saved in internal storage (Block 2340). In this block, it is the “meter time” which is saved rather than “universal time.” Meter time is the number of seconds elapsed since power-up and is not affected by system time synchronization's. After the start time is saved or if the aggregate state is other than Dist\_Start, then control returns to the top level routine along with the aggregate state.

**[00151]** Figure 24 depicts a flow chart showing the write\_disturbance\_outputs subroutine. It is first determined if the aggregate state is Dist\_Start (Block 2405). If so, a value of true is written to the DistState output register, a pulse is written to the DistStart output register and the event register is written with the event (Block 2410). This adds the event to the event log which will give the user information on the start of the sag/swell event. Control is then passed back to the top level routine (Figure 17). If the aggregate state is not Dist\_Start and not Dist\_End (Block 2415), then control is passed back to the top level routine (Figure 17).

**[00152]** If the aggregate state is any other value except Dist\_Start or Dist\_End, then for each configured voltage input (Block 2420), DistMin and DistMax output registers are written. The Disturbance Average is calculated according to the following formula and then written to the DistAve output register.

$$\text{Dist\_Ave} = 100 \times ((\text{sum of all voltage RMS values}) / \# \text{ of RMS values in the sum}) / V_{\text{nominal (RMS)}}$$

**[00153]** The Disturbance Energy is calculated according to the following formula and then written to the DistEnergy output register.

$$\text{Dist\_Energy} = 100 \times ((\Sigma(V_{\text{rms}}^2)/\# \text{ RMS values in sum})) / V_{\text{nominal(RMS)}}^2$$

**[00154]** For any non-configured voltage input, the corresponding output registers will be written with a Not\_Available value (Block 2425). Once all of the configured voltage inputs have been completed (Block 2430), a value of False is written to the DistState output register and the Disturbance duration is calculated by computing the elapsed time since Dist\_Start was first pulsed. The duration is then written to the DistDuration output register. In addition, a write pulse is sent to the DistEnd output register and the event register is written with the event cause set to the sag swell handle + “detected disturbance” (Block 2435). Control is then passed back to the top level routine (Figure 17).

**[00155]** Figure 25 depicts a flow chart showing the process\_sub-disturbance\_subroutine. If the aggregate state is Dist\_None (Block 2505), then the routine returns control to the top level (Figure 17). If the aggregate state is any other state then the following blocks are executed for each configured voltage input (Block 2510). If the input state is Dist\_End (Block 2515), then the sub-disturbance average is calculated and written to the sub-Dist Ave output register and the sub-disturbance duration output register is calculated and written to the Sub-DistDuration output register (Block 2520). A pulse is written to the Sub-Dist trigger output register and the following internal variables are set (Blocks 2525 and 2530):

Sub-dist ave = 0  
 Sub-dist start time – current meter time  
 Sub-dist num\_periods = 0  
 Sub-dist reference = input voltage value

**[00156]** If there are no other voltage inputs to check then control is returned to the top level routine (Block 2535) (Figure 17).

**[00157]** If the input state is Dist\_Start (Block 2540), then the sub-dist ave and sub-DistDuration output registers are set to not\_available (Block 2545). A pulse is written to the Sub-Dist trigger output register and the following internal variables are set (Blocks 2525 and 2530):

Sub-dist ave = 0

Sub-dist start time – current meter time

Sub-dist num\_periods = 0

Sub-dist reference = input voltage value

**[00158]** If there are no other voltage inputs to check then control is returned to the top level routine (Block 2535) (Figure 17).

**[00159]** If the input state is anything other than Dist\_None, Dist\_Start or Dist\_End then the stored reference voltage is compared to the input voltage (Block 2550). If the input voltage is outside the change criteria limits then the sub-disturbance average is calculated and written to the sub-Dist Ave output register and the sub-disturbance duration output register is calculated and written to the Sub-DistDuration output register (Block 2520). The change criteria limits are set by the user. A pulse is written to the Sub-Dist trigger output register and the following internal variables are set (Blocks 2525 and 2530):

Sub-dist ave = 0

Sub-dist start time = current meter time

Sub-dist num\_periods = 0

Sub-dist reference = input voltage value

**[00160]** If there are no other voltage inputs to check then control is returned to the top level routine (Block 2535) (Figure 17).

**[00161]** If the input voltage is not outside the change criteria limits (Block 2550) then control is returned to the top level routine (Figure 17).

**[00162]** Figure 26 shows a flow chart depicting the augment\_sub-disturbance\_data subroutine. If the disturbance state is Dist\_None (Block 2605), then control is passed back to the top level routine (Figure 17). If the disturbance state is any other value, then the following blocks are executed for each configured voltage input (Block 2610). The input voltage is normalized to the nominal voltage, added to a sub-disturbance voltage sum and stored internally (Block 2615). Finally, the variable num\_periods of sub-disturbance is incremented (Block 2620).

**[00163]** Figure 27 shows a flow chart depicting the augment\_disturbance\_data subroutine. If the aggregate state is any state but Dist\_Start or Dist\_Cont (Block 2705), then the initialize disturbance subroutine is called (Block 2710) (Figure 20 and detailed above) and control is passed back to the top level (Figure 17). If the aggregate state is

Dist\_Start or Dist\_Cont, then the following blocks are executed for each configured voltage input (Block 2715). If a new min or max was reached, then these values are stored internally (Blocks 2720 and 2725). The input voltage is normalized to the nominal voltage, added to the disturbance voltage sum and stored internally (Block 2730). The input voltage is normalized to the nominal voltage, then squared, added to the Energy sum and stored internally (Block 2735). Once all configured voltage inputs have been dealt with (Block 2740), the num\_periods of disturbance variable is incremented (Block 2745) and control is passed back to the top level routine (Figure 17).

d. Harmonic Detection and Calculation

**[00164]** Harmonics are voltage or current signals that are not at the desired fundamental frequency (often 50 or 60 Hz), but rather at some multiple of the fundamental frequency. It is important to detect harmonic frequencies present in the supplied power in order to select properly rated transformers for equipment as well as to effect an accurate power quality analysis and properly detect faults in the system. Referring now to Figure 28, in order to detect harmonic frequencies, the analog to digital converter synchronously samples voltage and current signals from the electric circuit (Block 2805). These samples are taken from all input channels. The preferred sampling rate is at least 64 samples per cycle although higher sampling rates can also be used. Typically, a sample rate which is synchronous to the fundamental frequency of the input voltage is used.

**[00165]** The digital signal processor determines the best channel for each input via autoranging (Block 2810) and transfers all of the samples and “best channel” information to the CPU using direct memory access techniques (Block 2815). Autoranging is described in more detail in the above referenced U.S. Pat. Application entitled “METHOD AND APPARATUS FOR AUTOMATICALLY CONTROLLED GAIN SWITCHING OF POWER MONITORS”. The best channel will be one which is non-saturated with the most resolution. The “best” samples from most optimal channel will then be copied to a new buffer on the CPU (Block 2820). On the CPU, a Fast Fourier Transform (FFT) algorithm is performed on one cycle of the “best” samples (Block 2825). One FFT is performed each second on a different input signal.

**[00166]** The FFT produces a set of complex pairs that can be manipulated by the CPU using techniques known in the art to produce the harmonic content for harmonics 2-63. These are measured as a percentage of the fundamental frequency. In addition, the magnitude and phase angle of the detected harmonic frequencies are also computed. The detected harmonics, magnitude and phase angle are recorded for access by the user. Further, the magnitude of the detected harmonics is compared to a pre-set threshold set by the user to determine if the presence of harmonics in the electric circuit exceeds the specification for normal power delivery. If the magnitude does exceed the threshold value, the waveform will be recorded (see detail below) for future diagnosis.

**[00167]** Harmonic Distortion measurements are indicative of the quality of the power being delivered to the customer. The 8500 measures harmonic distortion levels for individual harmonics up to the 63rd harmonic, as well as total harmonic distortion, total even harmonic distortion (all even harmonics), total odd harmonic distortion (all odd harmonics), and symmetrical components (see below).

**[00168]** In the exemplary revenue meter, harmonic calculations are based on the waveform sampled by the Digital Signal Processor (DSP). The DSP continuously samples the voltage and current gain channels at 128 samples per cycle, using three A/D converters. The data from the A/D converters is continuously transferred from the DSP to the CPU. All gain channels are transferred into six "half-cycle" DMA waveform buffers as a temporary storage area. The chain of those six buffers is used in a circular fashion. When the gain selection data becomes available, two cycles after the samples, the CPU uses it to locate the optimal data, and copy it to a harmonic calculation buffer. Optimal data will come from the gain channel with the highest voltage range which is not saturated.

**[00169]** The data in the harmonic calculation buffer consists of 1 cycle worth of raw A/D samples for each voltage and current channel. For each voltage and current channel, the raw sample data is converted to the frequency domain using a Fast Fourier Transform ("FFT"). The result from the FFT consists of an array of 63 complex numbers representing the complex voltage/current at the 1-63rd harmonics. These 63 complex numbers are then used to calculate the harmonic distortion measurements using the equations listed below.

$$H_N = \frac{\overline{FFT_N}}{\overline{FFT_1}} \quad HD_N = \frac{\overline{FFT_N}}{\overline{FFT_1} \cdot 100}$$

[00170] Where  $FFT_N$  is the nth complex number from the FFT result.  $HD_N$  is the harmonic distortion at the nth harmonic.

$$THD = \frac{\sqrt{\sum_{N=2}^{63} H_N^2}}{100} \quad TOHD = \frac{\sqrt{\sum_{N=3,5}^{63} H_N^2}}{100} \quad TEHD = \frac{\sqrt{\sum_{N=2,4}^{62} H_N^2}}{100}$$

[00171] Where THD is the total harmonic distortion, TOHD and TEHD are the total odd and even harmonic distortions respectively (Block 2830).

[00172] Once these values are computed, they are compared with user defined limits. If the values exceed the pre-defined limits, actions, as prescribed by the user are taken. This includes recording the waveform and/or reporting an error (Block 2840).

e. Symmetrical Component Detection and Calculation

[00173] The symmetrical component detection module provides information about unbalanced voltages and currents in a three phase power system. This allows identification or prediction of how electrical equipment might be affected. This information can be used to reduce induced circulations currents in motor windings, prevent equipment damage and prolong motor and transformer life. For a more detailed description of symmetrical components of electrical power, see “Protective Relaying Theory and Applications,” edited by Walter A. Elmore, pages 17-37 (1994).

[00174] The positive, negative and zero sequence components of the electric signal are computed using the equations listed below which use the fundamental complex FFT pairs for the voltage and current inputs. The positive sequence component consists of the three phasors, equal in magnitude, each 120 degrees apart with the same sequence (a-b-c) as the original phasors. The negative sequence component consists of three phasors, equal in magnitude, each 120 degrees apart with the opposite sequence (a-c-b) as the original phasors. The zero sequence component consists of three identical phasors (i.e. equal in magnitude and with no relative phase displacement). For a more detailed discussion of symmetrical components, see Stanley E. Zocholl, “An Introduction to

Symmetrical Components” (Schweitzer Engineering Laboratories, Inc., Pullman, Washington 1997).

**[00175]** In order to compute the zero sequence current or voltage, the fundamental voltage or current vector is computed from the magnitude and phase angle of the fundamental frequency of each phase of the electric circuit. These fundamental voltage or current vectors are then added together using vector addition.

**[00176]** To compute the positive sequence voltage or current, one phase’s fundamental voltage or current vector is shifted by plus 120 degrees. A second phase’s fundamental voltage or current vector is shifted by minus 120 degrees. These two phases plus the un-shifted third phase are then added together using vector addition. The computation of the negative sequence voltage or current is the same as the positive sequence except that the phase that was shifted by plus 120 degrees is now shifted by minus 120 degrees and the phase which was shifted by minus 120 degrees is now shifted by plus 120 degrees. It will be appreciated by those skilled in the art that these calculations are based on a 360 degree circle, and that subtracting 120 degrees from a vector is the same as adding 240 degrees, etc.

**[00177]** Once computed, the sequence voltages or currents can be compared with a threshold value to determine if there is a problem.

**[00178]** In the exemplary revenue meter, the FFT results from the harmonic content calculations are also used to calculate the symmetrical component vectors for both voltage and current (Refer to Figure 28, Block 2835). The symmetrical components consist of three vectors each for current and voltage. These three vectors are the zero component sequence vector, the positive component sequence vector, and the negative sequence component vector. The equations used to calculate each vector are illustrated below.

$$V_0 = \frac{1}{3}(FFT_{A,1} + FFT_{B,1} + FFT_{C,1})$$

Where  $V_0$  represents the zero sequence vector,

**[00179]**  $FFT_{A,1}$ ,  $FFT_{B,1}$ ,  $FFT_{C,1}$  represent the 1<sup>st</sup> complex number (fundamental) from the FFT result for phase A, B, C respectively.

$$V_1 = \frac{1}{3} (FFT_{A,1} + a \times FFT_{B,1} + a^2 \times FFT_{C,1})$$

[00180] Where  $V_1$  represents the positive sequence vector,  $a$  represent a 120 degrees phase shift operator and  $a^2$  represents a 240 degrees phase shift operator.

$$V_2 = \frac{1}{3} (FFT_{A,1} + a^2 \times FFT_{B,1} + a \times FFT_{C,1})$$

[00181] Where  $V_2$  represents the negative sequence vector.

#### IV. *Power Quality Event Handling*

##### a. Waveform Recording

[00182] Once a power quality event is detected, it is preferred that as much data as possible be recorded so that the event cause can be documented and diagnosed, either in real time (such as by the meter itself, or by a technician) or post-processed at a later time in order to ascertain possible causes of the event. As well, such diagnosis can be done either locally or remote from the meter. Not only must as much data be recorded about the event as is possible, but it must be recorded with sufficient detail to provide meaningful information long after the event as passed. In all of the above embodiments, when the particular power quality event is detected, recording of data about the power quality event will be immediately triggered so as to capture data early in the lifespan of the event. This is critical as some power quality events are only momentary, such as transient events.

[00183] The preferred method of capturing such power quality data is to record a waveform which represents the input voltages and currents from the different phases of the electric circuit as they change over time. The waveform is constructed by measuring and sampling the input voltages and currents and plotting these values with respect to time. It is also preferred that the waveform recorder be configurable depending on amount of information needed to be stored and level of detail required by the user. In the preferred embodiment 8500 Power Meter, waveform recording is implemented using the ION Waveform Recording Module, manufactured by Power Measurement, Ltd., Saanichton, British Columbia, Canada.

[00184] Referring now to Figure 29, a block diagram depicting the data flow in the preferred waveform recording module is shown. The voltages and currents for each phase in the three phase electric circuit first pass through the analog gain stages. These gain stages are described in more detail in the above referenced co-pending and commonly assigned U.S. Pat. Application entitled "METHOD AND APPARATUS FOR AUTOMATICALLY CONTROLLED GAIN SWITCHING OF POWER MONITORS". The gain stages are connected to the physical hardware input terminals of the meter which are connected to the three phase power system. The gain stages break up the input voltages and currents that come into the meter through the hardware terminals into multiple channels based on the voltage or current range of the input signal. There are 2 channels for each voltage input, Nominal and Overrange. In the preferred embodiment, the Nominal channel ranges from 0 – 156 Vrms and the Overrange channel ranges from 0 – 1000 Vrms. There are four channels for each current input, Creep, Underrange, Nominal and Overrange. In the preferred embodiment, the Creep channel ranges from 0 - .78 A, the Underrange channel ranges from 0 – 3.125 A, the Nominal channel ranges from 0 – 12.5 A and the Overrange channel ranges from 0 – 50A. Alternatively, one of ordinary skill in the art will recognize that other channel and range combinations are possible. For applications involving a fourth current input, the fourth current input is broken up into two channels, Underrange and Overrange. The Underrange channel ranges from 0 – 3.125 A and the Overrange channel ranges from 0 – 50 A. Each of the channels (twenty-four in the preferred embodiment) is connected to an analog to digital ("A/D") converter which samples each of the channels and converts the analog signals to digital samples. The A/D converter preferably converts the analog signals at a rate of 128 samples per cycle although other rates can be used. The digital samples are fed to the digital signal processor ("DSP") which stores the samples locally in a RAM buffer 2905. In the preferred embodiment, the RAM buffer 2905 consists of 6 buffers each capable of holding  $\frac{1}{2}$  cycle, although it will be appreciated that more or less buffers of larger or smaller sizes can also be used. The DSP then executes the autoranging routine, described in more detail in the above mentioned reference, to find the gain stage which provides the best resolution. This will be the first non-saturated channel for each input. On every  $\frac{1}{2}$  cycle, the CPU initiates a DMA transfer from the DSP RAM buffer 2905 to a RAM

buffer 2910 on the CPU side. The RAM buffer 2910 on the CPU side also includes six buffers each holding  $\frac{1}{2}$  cycle corresponding to the DSP RAM buffer 2905. The CPU RAM buffers 2910 are used in a circular fashion. Concurrently, on every  $\frac{1}{2}$  cycle, for every configured ION Waveform Module, the CPU transfers 64 samples representing  $\frac{1}{2}$  cycle of the first non-saturated channel and gain stage information for that channel to the Dynamic Memory Manager (“DMM”) 2915. Alternatively, a larger or smaller number of samples can be transferred. Further, the transfer can occur on a larger or smaller frequency. The samples may be decimated from 64 samples to some other power of two as specified in the ION Waveform Recorder Module Format Setup Register. The samples and gain stage information are initially stored in a working buffer in the DMM 2920. The working buffer can hold six sets of samples, each containing 64 samples or  $\frac{1}{2}$  cycle. Note that the working buffers can hold more or less data. There is preferably, one DMM working buffer 2920 for each ION Waveform Module that exists (typically fourteen). The working buffer 2920 format is dictated by the Format Setup Register of the corresponding ION Waveform Recorder Module. The sub-buffers of the working buffer 2920 are used in a circular fashion until a record pulse is received. When and if the ION Waveform Recorder Module receives a record pulse, the Module may instruct the DMM to start a new working buffer 2925 and save the existing working buffer 2920 into more permanent DMM storage for later retrieval by client software, such as the Pegasys Client. In this way, the Recorder Module continually records and re-uses buffer space until it is instructed to save what it has recorded. It then stops reusing the current working buffer 2920, and starts a new working buffer 2925. This continual recording methodology ensures that the context, before and after a power quality event is detected, will be saved for later analysis. This is useful, because later analysis may require knowing what the electrical signal look like up to the occurrence of the power quality event. Note that it will be apparent to those skilled in the art that the size of the data transfers and the size of the buffers can vary depending on the processor power, the available storage capacity, the desired power quality event context and the desired resolution of recording.

**[00185]** The low level waveform recorder firmware continuously transfers samples from the Digital Signal Processor (DSP) to the Central Processing Unit (CPU). Referring back to Figure 29, all gain channels are transferred into six “half cycle” DMA waveform

buffers 2920 as a temporary storage area. The chain of those six buffers is used in a circular fashion and forms the working buffer. When the gain selection data becomes available, two cycles after the samples, the CPU copies it to the user-configurable waveform recording buffers 2920 for the corresponding samples. Those buffers are under control of the Waveform Recording Module.

**[00186]** The Module can be enabled or disabled. If the module is disabled, the waveform data is not copied out of the DMA buffers which results in a reduction of the CPU load. However, the DMA portion of the waveform recorder continues to transfer samples from the DSP to the CPU in order to support harmonic calculations (detailed above). The preferred waveform recording module can be configured to save waveforms using 128, 64, 32 or 16 samples per cycle. This information is made available to the low level code which selects and copies required samples from the DMA buffers 2910 into the waveform recorder buffers 2915 to produce waveforms in the desired format.

**[00187]** The Waveform Recorder firmware is configured by the user to log waveforms of a specified duration at a specified resolution. The Waveform Recorder Module is used to take a snapshot of each input's voltage and/or current waveforms over a specific number of cycles as programmed by the user. Figures 30, 31 and 32 depict a flowchart of the Recorder module's operation. Generally, the blocks of these flow charts are executed on every half cycle with regard to the power frequency. The module first ascertains whether it needs to attempt to store a waveform during the current half-cycle of operation, prepare to store waveform in a subsequent half-cycle of operation or exit the current cycle of operation without storing a waveform.

**[00188]** If the module is to attempt to store a waveform in the current half-cycle, the module must determine if there is enough room in the waveform log to store the waveform and whether or not the current waveform is full. The current waveform is full if it contains enough cycles of data to make a full waveform. If both of these criteria are met, then the module will store the waveform with the appropriate trigger timestamp. The trigger timestamp indicates what triggered the recording of the waveform and the time of triggering. Next, output registers are updated to indicate how many waveforms can still be stored in the log (this is the Records\_Left output register) and whether the log is full or not (in the Log\_State output register).

**[00189]** The blocks of the module are executed no matter what operation is performed. The firmware checks to see if the Re-arm input has been pulsed. If this has been pulsed, then all of the waveforms will be cleared from the log, the output registers will be set such that they indicate that the log is empty and internal module variables will be initialized.

**[00190]** Referring now to Figures 30 and 31 in more detail, the blocks executed by the waveform recorder module are shown, for simplicity, as broken down into a main routine and three subroutines, A (Figure 30), B and C (Figure 31) which will be described below. Referring now to Figure 30, the main routine begins by determining whether or not the recorder module is enabled (Block 3002). If it is not enabled, the module will ignore record pulses by updating the `acknowledged_record_count` to equal the `current_record_count` which ensures that all record pulses are processed (Block 3004). Record pulses are the input to the Waveform recorder ION module which triggers recording. This ensures that any pulses that occur on the Record input are ignored when the module is disabled. The routine will then jump to subroutine C (see Figure 31 and below).

**[00191]** If the recorder module is enabled (Block 3002), it is then checked whether the `acknowledged_record_count` is equal to the `current_record_count` (Block 3006). If it is, then control transfers to subroutine C (See Figure 31 and below). If it is not equal, the `current_record_count` is stored in a local variable (Block 3008) and the routine then checks if the `record_delay_startup` is a nonzero value (Block 3010). If it is not non-zero, then control passes to subroutine A (See below). If the value is non-zero, the value of `waiting_for_full_record` is checked (Block 3012). If this value is True, indicating that the record is not yet full, then control passes to subroutine A (See below). If the value is false, that is the record is full, then it is checked if there is a `delay_pending` (Block 3014). If there is no delay pending then the following variables are set (Block 3016) and control passes to subroutine C (See Figure 31 and below):

`Delay_Counter = 1`

`Delay_Pending = True`

`Stored_Record_Timestamp = current timestamp value`

`Use_Stored_Timestamp = True`

**[00192]** If there is a delay pending, then it is determined if the `last_record_count` is less than the `current_record_count` and the value of the `use_second_stored_timestamp` variable is set to false (Block 3018). If these conditions are met, then `use_second_stored_timestamp` is set to true and `second_stored_record_timestamp` is set to the current time (Block 3020). After this block, or if the conditions are not met, the `delay_counter` is checked to see if it is greater than or equal to the value of the `record_delay_setup` register (Block 3022). If not, the `delay_counter` is incremented (Block 3024) and control passes to subroutine C (See Figure 31 and below). If `delay_counter` is greater than or equal to the value of the `record_delay_setup` register, then `delay_pending` is set to false, the `delay_counter` is set to zero (Block 3026) and control passes to subroutine A.

**[00193]** Subroutine A first checks to see if the Mode of operation is not `stop_when_full` or if the log is not full (Block 3050). If these conditions are met, the `records_left_output` register is decremented by one (Block 3052), the `acknowledged_record_count` is updated to equal the `current_record_count` (Block 3054) and control passes to subroutine C (See Figure 31 and below). If the mode of operation is `Stop_When_Full` or the log is full, then it is checked whether or not the current wave form record is full yet (Block 3056). If not, `waiting_for_full_record` is set to true (Block 3058) and `use_stored_timestamp` is checked (Block 3060). If `use_stored_timestamp` equals true, then it is checked whether or not `record_delay_setup` value is non-zero (Block 3062). If it is not non-zero, then control passes to subroutine C (See Figure 31 and below). If it is non-zero, then it is determined if the `last_record_count` is less than the `current_record_count` and the value of the `use_second_stored_timestamp` variable is set to false (Block 3064). If these conditions are met, then `use_second_stored_timestamp` is set to true and `second_stored_record_timestamp` is set to the current time (Block 3066). After this block, or if the conditions of Block 3064 are not met control passes to subroutine C (See Figure 31 and below). If `use_stored_timestamp` is false (Block 3060), then `stored_record_timestamp` is set to current timestamp value and `use_stored_timestamp` is set to true (Block 3068). Control then passes to subroutine C (See Figure 31 and below).

**[00194]** If the current waveform record is full, then `use_stored_timestamp` is checked (Block 3070). If this variable is False then the waveform timestamp is set to the current time stamp (Block 3072). If this variable is true, the waveform timestamp is set to the value of the `stored_record_timestamp` and the `use_stored_timestamp` variable is set to false (Block 3074). Next the scale and offset are obtained, waveform header information is written and the routine sets up the `Next_Waveform_Record` for recording (Block 3076).

**[00195]** Subroutine A then checks to see if the `record_delay_setup` register is a non-zero value (Block 3078). If it is not non-zero, or if the `use_second_stored_timestamp` is false (Block 3080), then the `acknowledged_record_count` is updated to equal the `current_record_count` to indicate that the record pulse has been dealt with (Block 3082). Finally the `waiting_for_full_record` is set to false (Block 3084) and control passes to subroutine B (See Figure 31 and below). If the `record_delay_setup` register is non-zero (Block 3078) and the `use_second_stored_timestamp` is true (Block 3080), then the `acknowledged_record_count` is updated to the `current_record_count` value minus one (Block 3086). `Waiting_for_full_record` is set to true (Block 3088), `use_stored_timestamp` is set to true, `use_second_stored_timestamp` is set to false, the value of the `second_stored_record_timestamp` is stored into the `stored_record_timestamp` (Block 3090) and control is passed to subroutine B.

**[00196]** Figure 31 shows a flow chart depicting the blocks of subroutine B of the waveform recording firmware. The mode of operation is first checked (Block 3102). If the mode of operation is “stop when full”, then the `records_left_output` register is decremented by one (Block 3104) and the log is checked to see if it is full (Block 3106). If the log is not full or if the mode of operation is not “stop when full”, then the log state is set to `not_full` (Block 3108), the next header of the next record is prepared for waveform recording (Block 3110), the record complete output register is pulsed (Block 3112) and control passes to subroutine C (See below). If the log is full (Block 3106), the log state is set to Full (Block 3114), the `record_complete_output` register is pulsed (Block 3112) and control passes to subroutine C.

**[00197]** Referring again to Figure 31, subroutine C first checks if the mode of operation is `stop_when_full` and if `Rearm` has been pulsed (Block 3150). If this is not

true, the routine sets the `last_record_count` to equal the `current_record_count` (Block 3152) and exits for the current interval. If the operation mode is “stop when full” and Rearm has been pulsed, then all waveforms are reset, the `LogState` is set to `Not_full` and the `stop_when_full` counter is set to indicate that the log is completely empty (Block 3154). The routine then initializes internal variables (Block 3156), sets the `records_left_output` register to the value of the `depth_setup` register (Block 3158) and updates the `acknowledged_rearm` count to equal the `current_rearm` count (Block 3160). Finally, the routine sets the `last_record_count` to equal the `current_record_count` (Block 3152) and exits for the current interval. In the preferred embodiment, this interval is preferably  $\frac{1}{2}$  cycle. Alternatively, longer or shorter intervals can be used.

**[00198]** Figure 32 shows a state diagram of the create and destroy behavior of the waveform recorder module with regards to waveforms. From the “factory initialization”, the next state is to Clear Input Handles, Initialize Output Registers, Initialize Internal Variables and Calculate Log Indices for faster module operation (State 3210). The module transitions to the next state where the Module and Registers are Destroyed and the Module is set to offline (State 3215). In response to “create module”, the Module and Registers are created and the Module is Offline (State 3220). In response to “destroy module”, Internal Variables are initialized and Input Handles are Cleared (State 3225) and the module transitions to State 3215. From State 3220, in response to “set module online”, the Recorder Module attempts to Sequence the Module for Execution (State 3230). This will succeed if the Depth and Format Setup Registers are set up correctly, the Source input is linked and there is enough processing power. From this state (State 3230), if the “Module Cannot Be Sequenced”, the Recorder Module transitions back to (State 3220). If the ‘Module Can Be Sequenced’, then the Recorder Module transitions to State 3235. In state 3235, Internal Variables are initialized, Acknowledged Record Count is set to Current Record Count, Acknowledged Rearm Count is set to Current Rearm Count, Log State is set to `Not_Full` if Depth is greater than zero, otherwise it is set to `Full` and the log index is calculated for faster module operation (State 3235). The Recorder Module then transitions to state 3240 where the module is set `ONLINE` (State 3240). From State 3240, in response to “Set Module Offline”, the Recorder Module

transitions to State 3220. From State 3240, in response to “Destroy Module”, the Recorder Module transitions to State 3225.

**[00199]** As was discussed above, the stored data can be analyzed in real time as well as post-processed at a later time. Further, the data can be transmitted to a location remote from the meter to undergo initial or further analysis. The meter provides communications means to transmit this data to the remote location. Exemplary communications means include modems and communications network connections. This communications may be via digital serial, digital parallel, analog, digital pulse, Ethernet, optical or other communications methodology as is known in the art. It will be appreciated that any form of communication of digital data is contemplated for use with the presently disclosed embodiments.

b. Direct Memory Access

**[00200]** Referring now to Figure 33, there is shown a block diagram depicting the direct memory access (“DMA”) firmware organization. Figure 34 is a timeline representation of DMA activity showing when the data transfers take place with respect to the sampling. The exemplary revenue meter’s sampling algorithm produces approximately 600kB of raw samples every second. This large amount of data needs to be pre-processed on the DSP and transferred to the CPU along with the results of the pre-processing. The data transfers must not compromise deadlines of any real time tasks running on the main CPU and must not disrupt continuous fixed rate sampling on the DSP. The samples produced by the sampling algorithm must be synchronized in time with the voltage and current RMS, power and other calculations to support operation of setpoint-triggered power line waveform recordings. The majority of the data is transferred from the DSP to the CPU, but there is also a need for a much smaller amount of data to be delivered from the CPU to the DSP.

**[00201]** The DMA implementation provides synchronized to sampling DMA data transfers which solves the problem of efficient data transfers between the DSP and CPU with minimal usage of clock cycles on both processors.

**[00202]** The DMA transfer requires minimal external hardware to operate. There is no need for use of costly dual port memories, which results in significant cost savings.

The synchronized to sampling DMA method also provides a higher overall data throughput with less CPU loading.

**[00203]** The synchronized to sampling DMA data transfer uses the passive DMA capabilities of the DSP processor and DMA controller functionality provided by the main CPU. The DSP executes its sampling algorithm and collects samples sorted by channel in buffers located in designated SRAM memory area. The buffers are big enough to hold 6 half cycles of data for each input gain channel. In addition to waveform buffers, there are two identical calculation buffers allocated for the pre-processing data transfers and data transfers from the CPU to the DSP (opposite direction to the main data flow). Identical buffer arrangement exists in the CPU DRAM memory.

**[00204]** The sampling occurs on 24 gain channels at a rate of 128 samples per cycle per channel which results in 3072 bytes of data every half cycle. Additional calculation buffers reserved for the pre-processing results hold 1024 bytes of data. A 64 byte data flow channel from the CPU to the DSP is reserved to allow direct memory access (“DMA”) from the CPU to the DSP. The total amount of data to be transferred in one half cycle is set to 4096 bytes.

**[00205]** During the DMA transfer the DSP processor is in IDLE state (no code execution), and its address, data and control bus are in TRI-STATE mode. To maintain the constant sampling rate, the DMA transfer must be fast enough and small enough to fit in between consecutive sample groups (every sample group consists of  $8 \times 3 = 24$  samples arriving simultaneously from three A/D converters). To achieve this, the DMA controller on the CPU executes four bursts of DMA transfers per every sample group which results in  $64 \times 4 = 256$  burst DMA transfers every half cycle. The total amount of data transferred per half cycle equals:

$$256 \text{ bursts/half cycle} \times 16 \text{ Bytes/burst} = 4096 \text{ Bytes/half cycle.}$$

**[00206]** The DMA transfer requests are issued by the DSP processor and are synchronized with the sampling algorithm in a way that maintains constant sampling rate. Depending on the line frequency from which the sampling rate is derived, the above scheme results in a data transfer rate of 174,456 bytes/second at 18Hz up to 589,824 bytes/second at 72Hz.

**[00207]** Due to the pre-processing that occurs on the DSP, the calculation data are delayed by 2 half cycles with respect to the corresponding samples. The 6 half cycle sample buffers are necessary to provide synchronization and correct operation of the waveform recorders.

**[00208]** Referring to Figure 33, the DSP Firmware consists of several independent routines. The DMA\_Interrupt\_Service routine 3310 (“DMA ISR”) receives the DMA burst start or end signal from the CPU and either puts the DSP into, or takes it out of, idle state. This routine also asserts subsequent DMA burst requests. The A/D\_Interrupt\_Service routine 3315 (“A/D ISR”) selects A/D channels for all of the A/D converters (A/D’s), collects and sorts samples from all of the A/D’s by gain channel and asserts the initial DMA burst request. This routine also starts subsequent A/D conversions in every sample group and controls operation of the DSP’s waveform and calculation buffers. Both the DMA 3310 and A/D 3315 ISR’s execute on the same priority level. They are synchronized in a way which guarantees a constant sampling rate.

**[00209]** The DSP firmware further includes a periodic timer interrupt routine 3320 and a half cycle task routine 3325. The periodic timer interrupt routine 3320 controls the sampling rate and starts the first conversion in every sample group. It also restarts the half cycle task routine. The half cycle task routine 3325 performs range selection which implements the autoranging functionality. The routine further controls the sliding window pre-processing for the CPU “one second task” routine and performs the sliding window calculations of high speed RMS, KW, KVR, KVA, peak and dc. RMS is root mean square, KW is kilowatts or active power, KVR is Kilovars or reactive power, KVA is kilovolt amperes or apparent power, peak is the instantaneous peak in every cycle and dc is direct current. Finally, the half cycle task routine sets up the sampling frequency which arrives from the CPU and processes other data arriving from the CPU such as the transient detection threshold or execution error information. The DSP half cycle task 3325 works with a corresponding half cycle task routine on the CPU. The periodic timer interrupt routine 3320 and half cycle task routine 3325 execute on the same priority level. The periodic timer interrupt routine 3320 controls restarts of the half cycle task routine 3325 and provides context save/restore services.

**[00210]** The DSP firmware further includes background tasks 3330 which monitor the processor load and drive diagnostic LED's.

**[00211]** A flow chart depicting an exemplary method for executing direct memory ("DMA") transfers is shown in Figure 35. A typical DMA transfer occurs as follows. The digital signal processor (DSP) asserts a data transfer request to the DMA transfer controller built into the Power PC processor (Block 3505). To initiate the data transfer, the DMA transfer controller then asserts the memory select line to select the DSP memory space (Block 3510). This causes assertion of the HOLD interrupt line to the DSP and assertion of the chip select line to the DSP memory. The DSP services the interrupt caused by the assertion of the HOLD line and enters an IDLE state which releases control of its data and address busses (Block 3515). Once in IDLE state, the DSP asserts the HOLDA (Hold Acknowledge) line (Block 3520). The combination of asserting the HOLD and HOLDA signals causes the data buffers to open and couple the DSP bus to the Power PC bus. The Power PC then waits for a prescribed delay after which it is guaranteed that the coupling is complete and the DSP is ready for the data transfer. The minimum wait time is dependent upon the CPU bus timing, the DSP HOLD/HOLDA signal timing and the bus coupling circuit timing. Alternatively, the WAIT signal line can be used to signal the Power PC that the DSP is ready. The DMA transfer controller in the Power PC then executes at least one burst data transfer (Block 3525). Upon completion of the burst data transfer, the DMA transfer controller de-asserts the memory select line which de-selects the DSP memory space (Block 3530). This causes the removal of the HOLD signal from the DSP input which further causes the buffers to close and de-couple the data busses. The removal of the HOLD signal causes an interrupt to the DSP. The DSP responds to the interrupt/removal of the HOLD signal by exiting from IDLE state (Block 3535). By the time the DSP exits from IDLE state, it is guaranteed that the data busses will be isolated. Again, this delay is dependent upon the CPU bus timing, the DSP HOLD/HOLDA signal timing and the bus coupling circuit timing. Alternatively, a signaling system can be used to indicate to the DSP that the data busses are isolated. Once out of IDLE state, the DSP acquires control of its data and address busses. Finally, the DMA transfer controller signals the Power PC that one or more data transfers was completed (Block 3540). It will be appreciated by those skilled

in the art that either processor can initiate the data transfer between its memory and the memory of the other processor.

**[00212]** Exemplary computer object code for implementing the above algorithms is included in microfiche appendix A and on the CD-ROM Appendix. This code contains all of the software modules disclosed in this specification and is intended to function on hardware as detailed in the schematics of microfiche appendix B and Figures 36A-56L. The following description will enable one of ordinary skill in the art to execute this code on the detailed hardware. In the hardware as detailed in appendix B, the object code is implemented in firmware stored in two 4 MB flash EEPROM flash memory chips. Preferably, these flash EEPROM's are DT28F320S5 EEPROM's manufactured by Intel, Inc. located in Sunnyvale, California. It will be appreciated that other flash memory chips can also be used as well as other non-volatile as well as volatile memory devices. The computer object code is compiled from source code written in the C language. It is presented in an S19 Srecord format which is defined in M68332BUG Debug Monitor User's Manual (1990) published by Motorola, Inc. The Srecords of the object code are first programmed into the two flash memory chips using a standard EEPROM programmer. This programming method is well known in the art. In addition, it will be appreciated that there are many techniques for programming object code into a memory device which can be used with the presently disclosed embodiments. One memory device is programmed with the object code starting at address 0x000000 to 0x3FFFFFF (hexadecimal), the other memory chip is programmed with the object code starting at 0x400000 to 0x7FFFFFFF. While the disclosed embodiments use two memory chips, a single memory device with sufficient capacity can also work. Utilizing the hardware as detailed in appendix B, with the code programmed as detailed above, the first memory chip is connected to Chip Select ("CS") 0 of the MPC821BGA (schematic notation: U1) processor and the second memory device is connected to CS 1. Jumpers J1 and J2 are added to connect CS 0 to CS\_FLSH1 and connect CS 1 to CS\_DSP. When power is applied to the given hardware, the processor will commence executing the object code at hexadecimal address 0x100.

**[00213]** Alternative methods of power quality monitoring, detection, quantification, communication and reporting are also contemplated. The disclosed embodiments

contemplate use of alternative meter inputs to enhance power quality assessment. For example, ANSI Standards define a form 76S and form 39S socket meters which include a fourth current input pair (designated I41 and I42) on the base of the meter. The purpose of the fourth current input pair is to allow the meter to directly measure the magnitude and/or phase of either the neutral or ground current.

**[00214]** Meters without a fourth current input pair can only derive the value of the neutral current mathematically. This mathematical derivation of neutral current may not be as accurate as a direct measurement if the electrical network star point is resistively coupled to ground. Meters equipped with a fourth current input pair are able to directly measure, with high precision, the magnitude and/or phase of the neutral or ground current. The ability to measure neutral or ground current is useful to modern commercial and industrial consumers using non-linear loads that cause high harmonic currents on the neutral conductor. Meters, so equipped with the fourth current input pair, can directly measure the harmonic content of the neutral or ground current, including the magnitude and phase angle of each harmonic component. This information is useful to the energy supplier and the consumer when attempting to identify the nature of the source causing the neutral or ground current.

**[00215]** In addition, with the direct measurement of neutral or ground current, the meter can provide detailed historical records of the current magnitude and phase over time. This information is useful when diagnosing subtle long-term trends in network or electrical system power quality. Further, a suitably equipped meter can provide real-time alarm and control signals if the magnitude or phase angle of the neutral or ground current differs from (exceeds or drops below) user-specified thresholds. The alarm and/or control signal can be used to prevent damage to plant and equipment when safety limits are exceeded.

**[00216]** Further, alternate applications of a fourth current input pair include: the ability to measure an additional single phase load across the voltage of either a Delta or Wye network; enabling one metering device to measure two 2-element Delta loads, or enable one device to measure several single phase loads fed by the same voltage.

**[00217]** In addition, although the ANSI specifications only specify a fourth current input pair, fifth, sixth or more current input pairs are contemplated. Further, current input

pairs can be implemented utilizing alternative inputs to the meter such as via “pig-tail” auxiliary cable inputs.

**[00218]** Further applications of a fourth (or more) current input pair include the ability to communicate in real time, the magnitude and phase angle of the 4<sup>th</sup> or additional current input. This communications may be via digital serial, digital parallel, analog, digital pulse, Ethernet, optical or other communications methodology as is known in the art.

**[00219]** These applications are useful because many electrical system problems and customer equipment problems are caused by poor power quality. Traditional electrical systems are designed to operate with balanced and linear loads. Under “normal” operating conditions, the neutral conductor is not required to carry currents as large as the phase conductors. Therefore, the current-capacity of the neutral conductor can be reduced to save costs.

**[00220]** When non-linear loads are connected to the electrical network, harmonic currents are induced in the phase and neutral conductors. This can cause the magnitude of the neutral current to be much greater than originally estimated for the design of the electrical system. In some cases, non-linear loads can cause the neutral current to exceed the current-carrying capacity of the neutral conductor. If this occurs, the safety of the plant and the equipment can be placed at risk because the neutral conductor could overload and cause a fire or other damage.

**[00221]** Prior to the point at which the magnitude of the neutral current reaches a dangerous limit, a meter that is capable of measuring the magnitude of the neutral current and continuously testing this magnitude against user-specified limits, can be used to generate an alarm or control signal. This alarm or control signal can be used to protect the electrical network from damage. In addition, the ability to measure and record the magnitude of the neutral current over time will allow system operators and users to monitor long term trends. This information allows designers to take pro-active steps to correct system abnormalities or to adjust the system design as required.

**[00222]** It is to be understood that a wide range of changes and modifications to the embodiments described above will be apparent to those skilled in the art, and are contemplated. It is therefore intended that the foregoing detailed description be regarded

as illustrative rather than limiting, and that it be understood that it is the following claims, including all equivalents, that are intended to define the spirit and scope of this invention.